A SYSTEMS-BASED APPROACH FOR SUSTAINABLE STEEL MANUFACTURING

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A SYSTEMS-BASED APPROACH TO SUSTAINABLE STEEL MANUFACTURING

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In loving memory of my grandfather, Charles B. Webb Jr.

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LIST OF SYMBOLS AND ABBREVIATIONS

BF	Blast Furnace
BOF	Basic Oxygen Furnace
BOFG	Basic Oxygen Furnace Gas
Ca	Calcium
CDQ	Coke Dry Quenching
Cl	Chloride
COD	Chemical Oxygen Demand
COG	Coke Oven Gas
CSI	Chinese Steel Industry
EAF	Electric Arc Furnace
EIP	Eco-Industrial Park
FW	Food Web
Mg	Magnesium
N	Nitrogen
Na	Sodium
P	Phosphorus
S	Sulfur
Si	Silicon
SS	Suspended Solids
TCE	Tonnes Carbon Equivalent
TRT	Top Gas Pressure Recovery Turbine

SUMMARY

China is by far the largest manufacturer of crude steel, producing over half of worldwide demand. Due to this, improvements to the Chinese steel industry can have far-ranging international benefits by decreasing its environmental impact. The focus of this thesis is on developing innovative systems-based solutions at different scales to help alleviate this burden. This is first accomplished by developing system-based technology solutions at the plant scale to increase water, energy and material efficiencies. From historical configurations until the present day, the steel manufacturing process structure and flows are modeled from an ecological perspective. Next, at a higher level, the focus transitions to transforming Chinese steel manufacturing plants into eco-industrial parks by means of industrial symbiosis with other companies and assessing the associated ecological metrics. In addition, improvement of these eco-industrial parks is investigated using functional roles found throughout nature but often absent within industrial networks. The use of constructed wetlands and pyrolysis are investigated to help alleviate the burden on the water network within steel manufacturing and increase material efficiencies. This multi-scale approach in the pursuit of sustainable steel manufacturing is unique in that it has not been attempted before and is not well understood.

CHAPTER 1. INTRODUCTION

Life has existed on Earth for more than 3.8 billion years. Through natural selection, organisms have continuously evolved across millennia into the natural systems that exist today. Some scientists propose that through the transformation of ecological principles to human engineered systems, there is potential to increase efficiency through the intelligent use of energy and resources while also reducing waste (Layton, Bras, & Weissburg, 2016; Layton, Reap, Bras, & Weissburg, 2012; Odum, 1969; J. J. Reap, 2009). Investigating the methods by which biological systems reached their environmentally sustainable state may enlighten engineers and scientists to a more astute way of sustainable systems formulation and lead to a more sustainable global community. A sustainable global community is one that meets the needs of the present generation without sacrificing those of future generations (Brundtland, 1987). Biologically inspired design and Industrial Ecology are two fields in science today that investigate the ways nature can provide insight to the creation and enhancement of sustainability and performance driven systems.

1.1 Motivation

The steel industry is a pillar of the Chinese economy, but rapid growth has come at cost to the environment (X. Yin & Chen, 2013). Chinese crude steel production has grown rapidly, increasing output of steel from 31.8 million tons in 1978 to 821.99 million tons in 2013 (International Iron and Steel Institute, 2005). The steel industry accounts for 18.3% of total energy consumption, and is one of the top three sources for greenhouse gas emissions within China (National Bureau of Statistics of China, 2012). In 2012, China accounted for 29% of the entire worlds CO2 emissions (Olivier, Janssens-Maenhout, Muntean, & Peters, 2013), and of these emissions approximately 12% is due directly to steel manufacturing (Li, Lei, & Pan, 2016). Thus, approximately 3.48% of global CO2 emissions originate from Chinese steel manufacturing. However, the Chinese Steel Industry (CSI) has made significant progress towards conserving energy and the environment through widespread conservation programs in their industrial sector in the Sixth (1981 – 1985), Seventh (1986-1990) Five-Year Plan (Liu, Sinton, Yang, Levine, & Ting, 1994) and more recently in 2009 with China's circular economy law (Matthews, Tang, & Tan, 2011). However, when one compares material and energy usage on an international scale, there is still considerable improvement to be made in Chinese industry. According to 2007 data, the IEA found that China could save 6.1 GJ/tonne crude steel through the adoption of best available technologies (International Energy Agency, 2010) and some scientists argue that the current high resource and energy demand of the CSI is currently unsustainable (Zhang & Wang, 2007).

All engineered products or processes affect the environment during their lifespan. Raw materials are extracted from the land, sea, and air then processed and manufactured into products for consumers and eventually disposed back into the environment. Due to this bond between engineered systems and the environment, to preserve valuable materials and resources for future generations, sustainable solutions are needed in engineering design. Engineering today is engaged in varying types of sustainable design using initiatives such as life-cycle analysis, pollution prevention, design for the environment, and design for recycling. These initiatives are the result of pursuing green engineering goals. These goals include waste reduction, materials management, pollution prevention, and product enhancement (Vallero & Braiser, 2008). However, these goals are subjective, interpreted by each designer or engineer individually rather than a standard across industry. Bio-inspired design, and subsequently industrial ecology, has the potential to remedy this by providing a standard to deduce the interactions between engineered systems and the environment.

1.2 Biologically Inspired Design, Industrial Ecology, and Food Webs

Through billions of years, nature has evolved to produce innovative designs through material and energy shortages. The field of bioinspired design uses these designs as inspiration in finding solutions to engineering problems. Biological systems are a valid source of inspiration in design due to natural systems often following principles of efficiency, adaptability, and multi-functionality (Weissburg & Yen, 2007). In engineering, Vogel states that biomimicry is the imitation, duplication, or general inspiration by nature to guide human innovation in the past (Vogel, 1999). An example of a successful application of biologically inspired design includes the tool Velcro, a wildly successful design developed by Georges de Mestral. Bioinspired design is unique in that it requires an understanding of the engineering and biological domains, but also the associations between the two. Some argue that the engineered world may benefit from nature's guidance in regards to the environment as well as performance (Benyus, 2002). However, one reason bioinspired design is not utilized more in practice is due to the challenges in developing these associations. This challenge is often attributed to the stark differences in mechanical and biological systems organization and construction to accomplish the same function (Glier, Tsenn, Linsey, & McAdams, 2011).

Though these challenges exist in bio-inspired design, a call for cooperative frameworks based upon a products life cycle (Bras, 1997) suggests a need for interaction with suppliers of recycled and refurbished materials and components, or the use of another manufacturer's waste (J. Reap, Baumeister, & Bras, 2005). Industrial ecology is an example of a field addressing this issue.

Material and energy flows are the fundamental properties affecting environmental sustainability because they are the main physical link between industrial and natural systems (Bailey, Allen, & Bras, 2004). Ecologists can derive multiple structural and flow metrics from these fluxes in ecosystems with a Food Web (FW). FW's are a graphical depiction of the linkages between actors within a given ecosystem with respect to materials and energy. Ecologists use this representation to generate an array of metrics, seeking to understand the links between ecosystem structure and the resulting behaviour of ecological systems (Fath & Halnes, 2007). These metrics describe a natural ecosystems structure, properties, and the predator-prey relationships (Roberts, 1976; Yodzis, 1980). Similarly, this approach may be used to investigate the ways nature can provide insight to the creation and enhancement of sustainable, performance-driven engineered systems. In this thesis, the food web principles and analysis are adapted to the steel industry in China to quantify impacts and potential areas of improvement within its structure, material flows, and its situational environment.

1.3 Thesis Organization and Research Questions

This thesis covers a wide range of topics regarding the sustainability of the CSI. Following the introduction, an in-depth literature review covers the historical and current state of the CSI and the government's efforts to strive for improvement. Highlighted in this review are some of the most pressing issues the CSI is presented with today and current research that is aimed to address these issues.

Building upon the understanding of the historical and current knowledge of the CSI, the foundation of food webs and Eco-Industrial Parks (EIPs) are established in the review to rate the ecological performance of these systems and their future pathways. Different structure and flow metrics are introduced and defined to provide context for this analysis. Finally, some of the challenges and shortcomings found throughout literature of current industrial networks and potential solutions are highlighted.

A model is then proposed to demonstrate the progress of the CSI's past, present, and proposed future modifications using data available from industry partners and literature. Emphasis is placed on future modifications to the CSI production routes, as the Chinese government is searching for the best mechanisms to remain the world's steel supplier but by doing so in the most environmentally conscientious way possible. A proposed EIP configuration from industry is modelled to demonstrate the improvements in structure from current day and the past configurations. Ultimately, using recommendations from literature, a redesign of an expanded EIP is investigated to show possible alternate configurations that could benefit industry. The major research question that needs addressing from our models are:

- *From an ecological perspective, has the CSI improved over time and to what degree?*

- *With the implementation of the EIP structure within the CSI, does this improve the structure from an ecological perspective?*
- *Can we alter the EIP configuration in industry to produce better results through incorporation of functional roles found in natural systems but often absent within industrial systems?*

This thesis concludes with a summary of the problems caused by the steel industry, the progress through time attempting to fix these issues, the model this thesis uses to quantify improvements from an ecological perspective, and future research recommendations moving forward.

CHAPTER 2. LITERATURE REVIEW

2.1 Historical Usage and Claims in Industrial Ecology

Industrial ecology is a new integrated science that systematically designs, projects, and controls the framework of human engineered systems per the harmonious principles developed through natural systems evolution. Industrial ecology emphasizes the comprehensive utilization of resources, integration of technology, and the proliferation of inter-process linkages through communal symbiosis. This approach uncovers the metabolism of material and energy flow in engineered systems. When examining these systems, each mechanism within a manufacturing process is treated as an inter-dependent and inter-connective element with the larger industrial processes. Through this approach, one can observe how industrial ecology is an applied science that is geared to not only improve industrial processes economically, but also with respect to the environment.

The past hundred years is a period of fully developed industry and technology in the world. However, the uncontrolled consumption of resources and energy for mass production without considering the outcomes of mass abandonment, has caused massive deterioration of the environment. These conditions are harmful to sustainable development of industry. Some scientists and engineers have recognized that these historical issues plaguing industry permeate to the international steel industry (X. Yin & Chen, 2013).

Nature can give fundamental insight for designing sustainable manufacturing systems (Layton et al., 2012). This is due to ecological systems being prime examples of complex and interconnected systems. These interacting species can be used as sustainable examples in the design of industrial networks, also known as eco-industrial parks (Frosch & Gallopoulos, 1989). The eco-industrial parks organize industry to be co-located to maximize the communal efficiencies by exchanging wastes generated by specific industries and use them as feedstocks in others, just as observed in biological species in natural ecosystems. A well-known example of such symbiosis is the Kalundborg eco-industrial park in Kalundborg, Denmark (Ehrenfeld & Gertler, 1997).

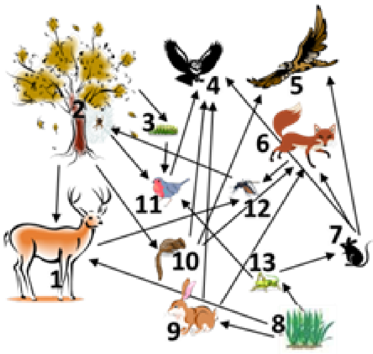
2.1.1.1 The Importance of Key Functional Roles in Industrial Ecology

Within every natural ecosystem there are multiple key functional roles. Primary producers, consumers, decomposers, and the physical environment all contribute to what constitutes an ecological community (Mitsch & Jørgensen, 2003). In natural ecosystems, the amount of internal cycling is strongly influenced by the presence of the decomposer role, an actor often called a detritivore in ecology. Over half of the material flows in natural food webs are connected to a detritivore which breaks down unused material by higher level species known as detritus and returns is back into the system, where in traditional industry this functional role is often lacking or missing altogether (Layton et al., 2016). Some scientists and engineers argue that even limited connections to an actor that functions similarly would greatly enhance the efficiency of eco-industrial parks (Layton, Bras, & Weissburg, 2017). In this thesis, we investigate the incorporation of the decomposer role and its effects on traditional performance and ecological metrics.

2.2 Ecological Metrics

By using a systems-based analysis of the industrial landscape, one can systematically model composite processes to design, project, and control the mechanisms which produces a system that moves materials and energy more efficiently. In addition, this investigation unveils the stressors and response mechanisms of resource exploitation throughout the modelled system as well as their environmental impacts. Engineers can use this analysis to make modifications to the industrial structure by designing systems that more closely resemble a healthy ecosystem. Past examples of using measurements of system behavior to influence design changes within the system has been well documented (Bailey et al., 2004; Bodini & Bondavalli, 2002; Layton et al., 2016). Using the analyzed systems metrics, more efficient and effective network configurations have been found to meet the traditional network design goals of reduced cost and increased efficiency(Layton et al., 2012; J. J. Reap, 2009).

The calculation of these metrics involves the identification of predators, prey and the links they represent in a FW. This method of representation can be shown in matrix form by ones denoting a successful link and zero denoting the absence of a link with columns representing predators and rows representing prey (i.e. $f_{ij} = 1$ represents a link between prey (i) and predator (j); Figure 1). The species are numbered and listed above and beside the matrix to show they are the same species across rows and columns as demonstrated in Figure 1.



$$F = \text{prey} \begin{array}{c} \\ 1\\2\\3\\4\\5\\6\\7\\8\\9\\10\\11\\12\\13 \end{array} \overset{\text{predators}}{\begin{array}{c} \begin{array}{ccccccccccccc} 1&2&3&4&5&6&7&8&9&10&11&12&13 \end{array} \\ \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&1&0\\ 1&0&1&0&0&0&0&0&0&1&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&1&0\\ 0&0&0&1&1&1&0&0&0&0&0&0&0\\ 1&0&0&0&0&0&0&0&1&0&0&0&1\\ 0&0&0&1&0&1&0&0&0&0&0&0&0\\ 0&0&0&1&1&1&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&1&0&0 \end{bmatrix} \end{array}}$$

Figure 1 - Left: a hypothetical food web with a number corresponding to the species. Right: the FW matrix representation of the hypothetical food web. Figure adapted from (Layton et al., 2016).

Ecologists may also incorporate flow based analysis in the understanding of ecological systems. Flow based metrics calculations require knowledge of both structural information and flow based information. A flow based analysis follows four different classes of flow:

1. Inputs that enter across system boundaries

2. Flows that move between actors within the system boundaries

3. Exports that leave across the system boundaries

4. Dissipation losses (Most associated with water or energy)

In contrast to the calculations of the structural metrics, flow metric calculations use a $N+3$ x $N+3$ food web flow matrix that includes inputs from outside the system (row zero), exports to outside the system (column *N+1*), and losses from the system (column *N+2*) Figure 2. A flow from actor *i* to actor *j* is represented as a real value by t_{ij}, which is the i^{th} row and j^{th} column entry in this matrix. A value of zero for t_{ij} means no material or energy flow occurs from actor *i* to *j* and, thus, no link exists.

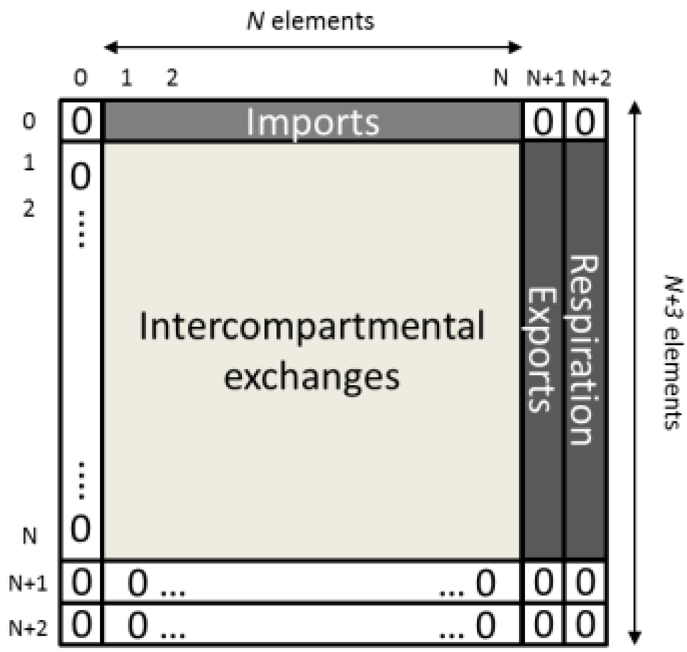


Figure 2 - Flow Based Matrix Example. Figure adapted from (Scotti, Bondavalli, Bodini, & Allesina, 2009)

2.2.1 Structure-Based Metrics

<u>*Number of Species (N):*</u> The total number of species in a FW. This term is also commonly denoted as "species richness" and can be represented by the number of rows or columns in a FW matrix (Briand, 1983).

Number of Links (L): The number of direct links between species in a FW. This term is represented by the number of nonzero interactions in the FW matrix (Briand, 1983).

$$L = \sum_{i=1}^{m} \sum_{j=1}^{n} f_{ij} \tag{1}$$

Linkage Density (L_D): The ratio of the total number of links to the total number of species within a network (Schoener, 1989).

$$L_D = {}^{L}/_{N} \tag{2}$$

Prey (n_{prey}): The species which are consumed by at least one other species. This relationship is represented by the number of non-zero rows within a FW matrix (Schoener, 1989).

$$f_{row}(i) = \begin{cases} 1 \; for \; \sum_{j=1}^{n} f_{ij} > 0 \\ 0 \; for \; \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{3}$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i)$$

Predator ($n_{predator}$): The species which consumes at least one other species. This relationship is represented by the number of non-zero columns in a FW matrix (Schoener, 1989).

$$f_{col}(j) = \begin{cases} 1\ for \sum_{i=1}^{m} f_{ij} > 0 \\ 0\ for \sum_{i=1}^{m} f_{ij} = 0 \end{cases}$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \tag{4}$$

Prey to Predator Ratio (P_R): The ratio of the number of species consumed by another species to the number of species that consume another species.

$$P_R = {}^{n_{prey}}/_{n_{predator}} \tag{5}$$

Generalization (G): The average number of prey consumed per predator within the FW. This is calculated by the summation of the columns in a FW matrix, and then dividing the number of columns with non-zero elements ($n_{predators}$).

$$G = {}^{L}/_{n_{predator}} \tag{6}$$

Vulnerability (V): The average number of predators per prey in a FW. This is calculated by the summation of the rows in a FW, then dividing by the number of rows with non-zero elements (n_{prey}).

$$V = {}^{L}/_{n_{prey}} \tag{7}$$

Cyclicity (λ_{max}): A measure of the strength and presence of cyclic pathways present within the system. This is calculated by finding the maximum real eigenvalue of the transpose of the FW matrix. The transpose of the FW matrix is A (Allesina, Bondavalli, & Scharler, 2005; Fath & Halnes, 2007)

$$\lambda_{max} = max, real\ eigenvalue\ solution\ to: 0 = \det(\boldsymbol{A} - \lambda \boldsymbol{I}) \tag{8}$$

Connectance (C): The number of actual direct interactions (L) in a FW divided by the total number of possible interactions (N^2). If one forbids cannibalism, then the number of possible interactions is diminished, resulting in the denominator becoming the fraction of non-zero off-diagonal elements in the FW (Briand, 1983; Warren, 1990; Yodzis, 1980).

$$C = {}^{L}/_{N}\,2 \tag{9}$$

2.2.2 Flow-Based Metrics

Total System Throughput (TSTp): The sum of all flows in an ecosystem. TSTp is a measure of size or level of activity (similar to GNP, which estimates the overall economic activity of a nation) (Bodini & Bondavalli, 2002; Bodini, Bondavalli, & Allesina, 2012; Robert E Ulanowicz, 2000).

$$TSTp = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \tag{10}$$

Average Mutual Information (AMI): The degree of specialization in the system or the amount of constraints on the materials and or energy flow. AMI has been suggested as being indicative for the developmental status, or level of system maturity of an ecosystem (Bodini & Bondavalli, 2002)

$$AMI = -k \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} \frac{t_{ij}}{TSTp} \cdot log_2 \left[\frac{t_{ij} \cdot TSTp}{\left(\sum_{j=0}^{N+2} t_{ij}\right)\left(\sum_{i=0}^{N+2} t_{ij}\right)} \right] \tag{11}$$

<u>System Ascendency (ASC):</u> Measures the amount of medium that an ecosystem distributes in an efficient way. Thus, providing a single measurement of growth and development inherent in the system (Bodini & Bondavalli, 2002; Bodini et al., 2012; Robert E Ulanowicz, 2000).

$$ASC = AMI \cdot TSTp \tag{12}$$

<u>Development Capacity (DC):</u> The maximum potential that a system has at its disposal to achieve further improvements, and serves as an upper bound for ASC (Bodini et al., 2012; Robert E Ulanowicz, 2000).

$$DC = -1 \cdot \sum_{i=0}^{N+2} \left[\left(\sum_{j=0}^{N+2} t_{ij} \right) \cdot log_2 \left(\sum_{j=0}^{N+2} t_{ij} \right) \right] \tag{13}$$

$$DC \geq ASC \geq 0$$

<u>Total System Overhead (TSO):</u> TSO pertains to redundant flows in the network and might be an indicator as to the point of optimality between flexibility and efficiency (Bodini & Bondavalli, 2002; Bodini et al., 2012; Robert E Ulanowicz, 2000)

$$TSO = DC - ASC \tag{14}$$

<u>Cycling Index (CI) or Finn Cycling Index (FCI):</u> Dimensionless number that accounts for percentage of all fluxes generated by cycling, or the fraction of total activity in the system that is devoted to cycling (Bodini & Bondavalli, 2002; Finn, 1977).

$$TST_C = \sum_{j=1}^{n} \left(\frac{t_{jj} - 1}{t_{jj}} \right) T_j$$

$$CI = \frac{TST_C}{TST_p} \tag{15}$$

<u>*Mean Path Length (MPL) or Average Path Length (APL):*</u> The number of actors "visited" by a material or energy flow (Finn, 1977).

$$MPL = {TST_p} \Big/ {\sum_{j=0}^{N+2} t_{0j}} \tag{16}$$

<u>*Robustness (R):*</u> Measures the relationship between *ASC* and *DC*, or the organizational constraints in the system vs redundancy, normalizing the systems "degree of order" (Fath, 2014; Robert E Ulanowicz, 2000)

$$R = -k \left(\frac{ASC}{DC} \right) log_2 \left(\frac{ASC}{DC} \right) \tag{17}$$

Figure 3 represents the balance between redundancy and efficiency.

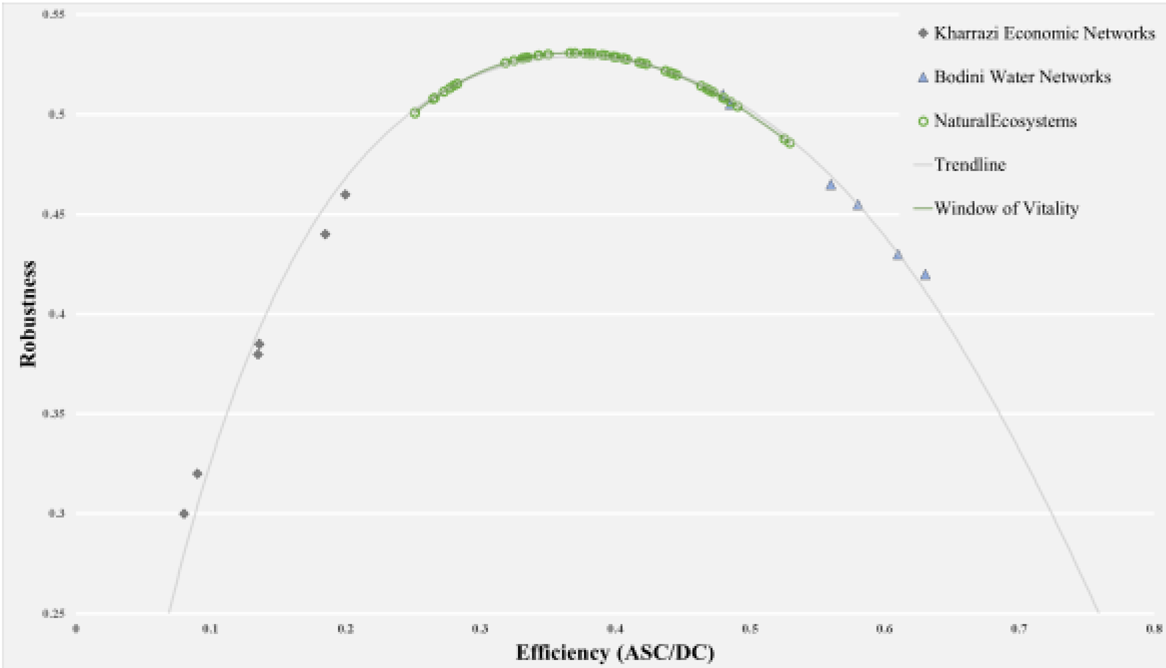


Figure 3 - Efficiency vs. Robustness Curve

Robustness indicates lower constraints on flows in a system, which allow a system to maintain function when faced with perturbations. On the contrary, and increase *ASC/DC* indicates higher constraints on flows resulting in greater efficiency.

The observation that most ecological systems, particularly those that are deemed healthy by independent criteria, occupy the balance of efficiency and robustness. When *ASC/DC* is plotted against *R*, the peak demonstrates this balance. Layton et al. (2016) combined economic resource networks, water networks (Bodini et al., 2012), economic networks (Fath, 2014), world zinc network (Graedel et al., 2004), and 93 ecosystems and plotted their results on this curve. Figure 3 demonstrates the water networks, 93 ecosystems, and economic networks. Highly redundant systems such as the Kharazi

Economic Networks demonstrate high redundancy and low efficiencies, while highly efficient industries such as Bodini's Italian Municipalities reflect lower robustness but higher efficiencies. Robert E. Ulanowicz, Holt, and Barfield (2014) termed the peak inhabited by the natural ecosystems as the "window of vitality", which can be used as a benchmark in the sustainable balance between efficiency and redundancy.

2.3 Chinese Steel Manufacturing

Traditionally, steel manufacturing involves two kinds of processes. These processes include Blast Furnace (BF)-Basic Oxygen Furnace (BOF) which is named the "long process" or the Electric Arc Furnace (EAF) which is named the "short process". The long process involves processes such as sintering, coking, and use of the BF which pollute far greater amounts than the short process, which is more reliant on scrap. Alternatively, there is also a direct smelting reduction route that is not utilized on a wide scale. Figure 4 illustrates the current steel production routes available throughout the world today.

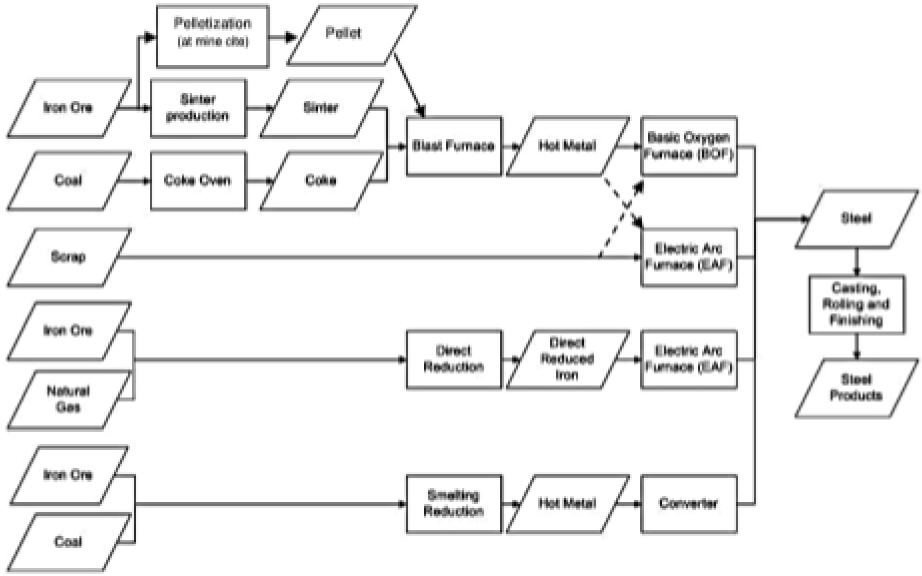


Figure 4 - Steel Production Routes. Figure Adapted from (Hasanbeigi, Jiang, & Price, 2013)

China's high energy consumption and heavy pollution within its steel manufacturing industry is primarily due to the lack of scrap supply, resulting in over 91% of the steel manufacturing reliant upon the long process (China Iron and Steel Association, 2011). Realizing the overwhelming majority of steel being reliant upon the long process, this thesis will investigate the steel product lifecycle from a systems level, evaluating the system's structure using ecologically-inspired metrics to provide quantitative insight into potential areas for sustainable improvement. Figure 5 illustrates the raw materials and differing processes involved with the BOF steel manufacturing route.

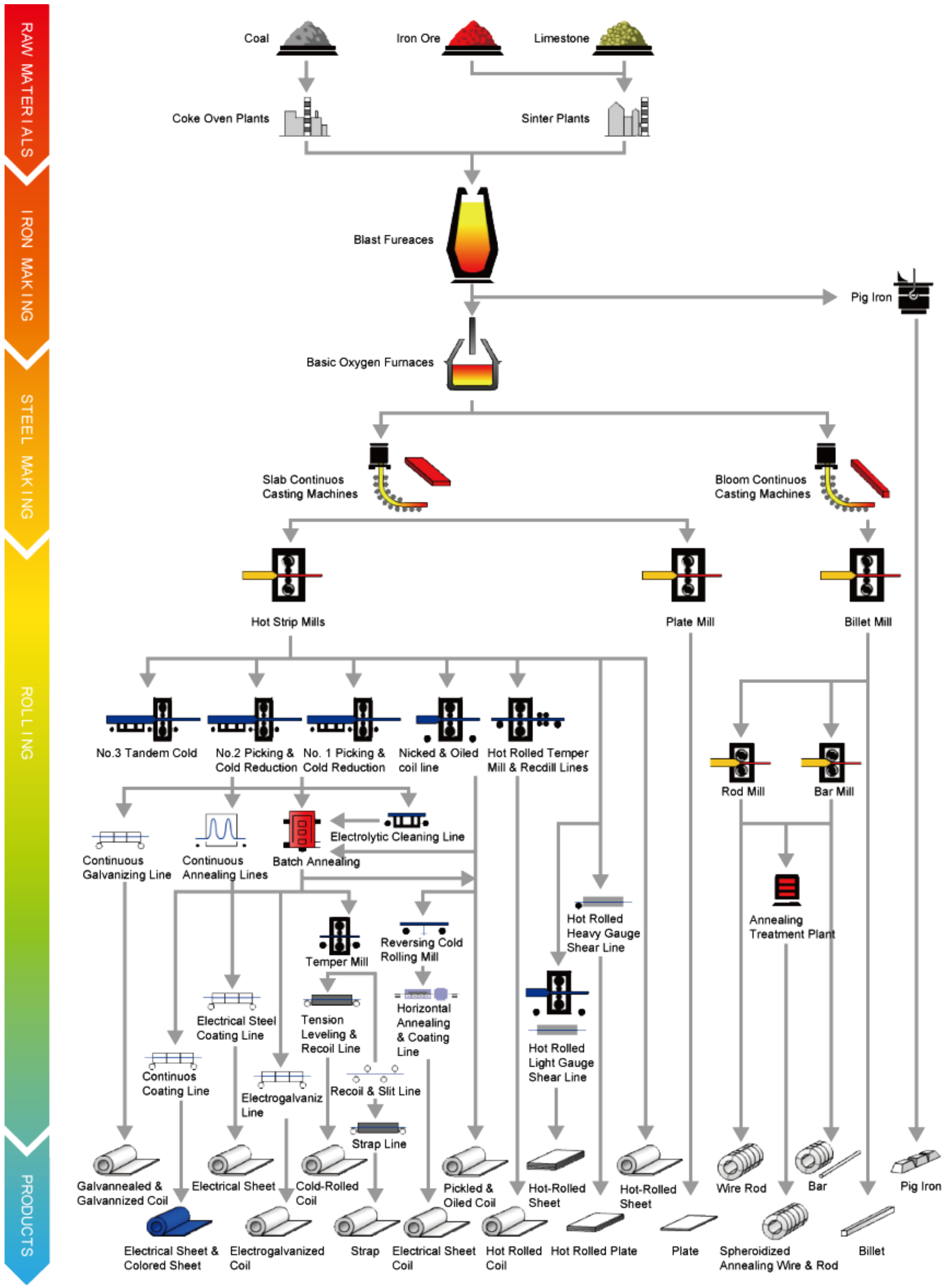


Figure 5 - BOF Steelmaking Production Process

Figure 5 demonstrates the process order, layout, and raw materials used in the historical BOF steel making process. The raw material stores consist of raw water, lime, coal, and iron ore. The main processes contributing flows to the long process of steel manufacturing include the coking plant, sintering plant, lime plant, oxygen plant and water treatment plant. The core functions after the contributing flows involved in the long process include coke making, sintering, BF iron-making, BOF steel making, and steel rolling. Secondary processes that vary from plant to plant include types of hot metal pre-treatment, differing types of secondary metallurgy, and methods of reheating before the rolling or plate mills.

In coke making, a carbon product is formed by the thermal distillation of coal at high temperatures in the absence of air. Coke is usually produced in a series of coke ovens. Coke's main function in the iron making process is to reduce the atmosphere in a BF, but also acts as a source of fuel. A key characteristic in coke is its porosity, which allows for gas exchanges throughout the BF. Newer steel plants use the combustion waste heat in the coke-making process to generate steam and electricity.

In sintering, iron-ore fines, iron laden wastes, and dust from the coke manufacturing process are blended and combusted. The heat from the process fuses these constituents together to form lumps of sinter. This sinter is then used as a charging component in the blast furnace. The sintering process as a whole allows for wastes generated in the iron and steel making process to be recycled that would otherwise be discarded as unusable.

A component not pictured in Figure 5 is pelletizing. In pelletizing, iron ore is crushed and ground to remove impurities. The resulting ore is mixed with a binding agent and then heated to create pellets. These pellets are used in both the BF and BOF. Due to this process occurring at mining sites, in modelling it is usually accounted for as a raw material input.

In the BF, iron ore, coke, and limestone form alternating layers in the furnace atop a bed of incandescent coke. Hot air, or blast, is blown through small openings and through this bed of coke. The coke combusts, producing heat and gasses. The heat melts the sinter charge and the carbon monoxide gasses produced remove the oxygen from the iron ore. This process combined forms hot metal which flows to the bottom of the blast furnace and through the coke bed. The hot metal is held here until transported to the BOF where it is further refined into steel. Iron making using a BF is the most energy intensive process and is also the largest emitter of CO2 in steel manufacturing (American Iron and Steel Institute, 1999).

When the hot metal is then transferred to the BOF, the metal is then refined into steel. Oxygen is added to remove the 4% carbon remaining in the molten metal after leaving the BF. The BOF process does not consume or produce energy (International Energy Agency, 2007). After the metal is refined into steel, it is transferred to the continuous casting process and subsequently to rolling and finishing.

During continuous casting, steel is formed into general shapes such as slabs, blooms, billets, or rounds. After casting, specific products can be formed in rolling mills to produce final shapes such as strips, rails, rods, bars, or sheets. The steel from continuous casting is reheated before rolling, which consumes electricity in addition to further the shaping of the steel. Finally, the products from rolling can be further processed to hot forming, cold rolling, annealing, galvanizing, and other refined products.

2.3.1 Challenges and Limitations in the Chinese Steel Industry

Some scientists argue the current CSI is progressing on an unsustainable route (Zhang & Wang, 2007). When evaluating this assertion, one cannot overlook the importance of the entire life cycle of the finished product. This importance stems from steel being the most recycled material in the world (Bureau of International Recycling Ferrous Division, 2015). Metals do not degrade due to recycling, thus the flows of materials exiting the steel manufacturing process and then being recycled later in the products life in the form of scrap is important in the flow analysis especially in regards to feedback loops of material flows. Figure 6 illustrates the inputs of energy, water, raw materials, and scrap into the steel manufacturing process along with the other processes involved from the lifecycle of steel.

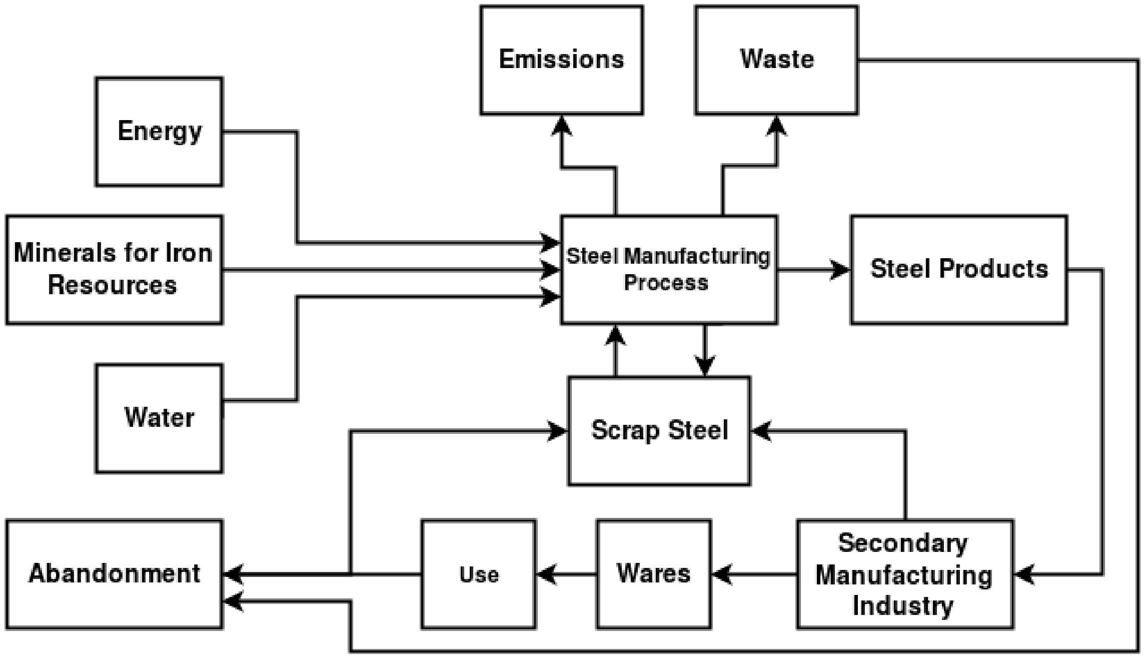


Figure 6 - Life Cycle of Steel

Understanding the full impact and uses outside of the system boundaries of the steel manufacturing process results in a more accurate analysis of the systems within the network structure. To accurately model the changes of the steel manufacturing process one must first define the system boundaries. Observing the transfer of core materials and energy, one can then investigate how the embedded processes within the boundaries have progressed throughout time.

2.3.2 Historical Progress of the Chinese Steel Industry

There have been major gains in efficiency in the CSI from the year 1980. Energy consumption per tonne of steel dropped 20.9% from 1285 kgce/t to 1017 kgce/t from 1980 to 1990 (Sun, Cai, & Ye, 2013). During this time, China developed strategies to improve energy efficiency and energy conservation management, offer financial incentives, direct

R&D, initiate IT services, and improve education and training (Sinton & Levine, 1998). Many of these strategies focus on optimization of the steel making process such as retiring energy intensive mechanical and electrical devices, incorporation of continuous casting technologies, controls technologies, and investigating the use of by-product gasses as fuel.

2.3.3 Current State of the Chinese Steel Industry

Since 1990, major gains in energy conservation in CSI came about through structural adjustment as well as energy and material flow optimization. The CSI focused on waste heat recovery and re-use technology, raw material and fuel pre-treatment technologies, plant layout optimization, energy management and controls using automation technology (Sun et al., 2013).

One of the largest gains in efficiency in the BOF process has occurred through using byproduct gasses and the optimization of material flows. The byproduct gasses are transported to boilers in the power plant to produce steam, which is then converted to electricity through turbines in addition to reuse in the reheating furnace. This reduces the overall energy consumption used in the steel making process, and is consistent with literature in direct observations showing that in 2007, 90% of the BF's larger than 1000 m^3 were equipped with a Top gas pressure Recovery Turbine (TRT). Further, by the end of 2006, 77% of key Chinese steel enterprises had also installed BFG recovery equipment and 64% had installed recovery equipment for other gas recovery such as Coke Oven Gas (COG) and Basic Oxygen Furnace Gas (BOFG) (Song & Liu, 2012). Also, by the end of 2004, nearly 25% of the CSI had Coke Dry Quenching (CDQ) units installed and in operation (International Energy Agency, 2007; Song & Liu, 2012). The addition of CDQ reduces the amount of water consumed by the steel making process and improves the overall water quality used throughout the manufacturing process.

2.4 Summary of Literature Review

In this review, a brief introduction to industrial ecology is presented. Some of the history behind industrial ecology is examined, its applicability to industrial analysis with the use of food webs, and the metrics used in ecological network analysis are defined. Also discussed is the important role decomposers play in industrial network design.

In addition to industrial ecology, the steel making manufacturing process and the CSI are investigated. The major manufacturing routes, processes, and sub-processes are discussed in detail. Next, the historical and current state of steel manufacturing in China is assessed and major improvements from the historical manufacturing process to current process are highlighted. Finally, some of the challenges associated with steel manufacturing today, particularly in China, are presented.

CHAPTER 3. SYSTEM DESCRIPTION

3.1 Steel Industry: Plant Scale Analysis

In this section, the CSI models structure and materials flow construction from past until present is discussed, assumptions listed, and data is presented.

3.1.1 Historical Model Data Acquisition and Assumptions

For the historical analysis, the major process level material flow values were chosen from the Yearbook of China's Steel Industry (Mettalurgical Economic R&D Centre of China, 1988) for the 1988 Anshan Iron and Steel Corporation's BOF plants statistics. Values such as coking rate, continuous casting yield, external scrap use fractions and each stage material flow values in the production levels as well as all model configurations are available and listed in A.1 CSI Historical Data. However, some values needed to be acquired from sources throughout literature as a single source could not be located.

The assumptions of the historical model are as follows:

- The use of by-product gasses such as Coke Oven Gas (COG), Blast Furnace Gas (BFG), and Basic Oxygen Furnace Gas (BOFG) are not utilized for power generation in 1988 and are instead released to the environment (Sun et al., 2013)

- The use of pellets, anthracite, oxygen blast air from oxygen generation plant, or lime is not used in iron making. (Rosst & Feng, 1991)

- Water is consumed at 210m ^{3} per tonne crude steel as estimate from 1998, due to lack of data in 1988 (The Editorial Board of the Yearbook of Iron and Steel Industry of China (ISIC), 1998)

- BOF slag is assumed to be 0.0085 tonne per tonne crude steel due to lack of data in 1988 (R. Yin, 2013)

- Mill scale is not recycled into the sinter plant (Umadevi, Kumar, Mahapatra, Babu, & Ranjan, 2009)

- The distribution of water flows throughout the plant are the same percentages from current day though usage rates differ greatly (Worrell, Blinde, Neelis, Blomen, & Masanet, 2010)

- The flows from the lime plant, iron ore powder and lime from the raw material yard to the sinter plant remain unchanged from current day amounts

- The co-location of industries that could benefit from the products or waste streams of this historical plant are outside of the historical system boundaries

- Due to the steel manufacturing fuel use being represented largely by coal, a conversion of off-gasses into coal equivalent is assumed

The assumptions above are largely due to data scarcity during the late 1980's for the CSI. Where values must be assumed (lime flows, emission amounts), conservative estimates were taken as to not distort the model.

3.1.2 Historical Model Structure and Flow Construction

The simplified structural configuration of the historical model is demonstrated in Figure 7.

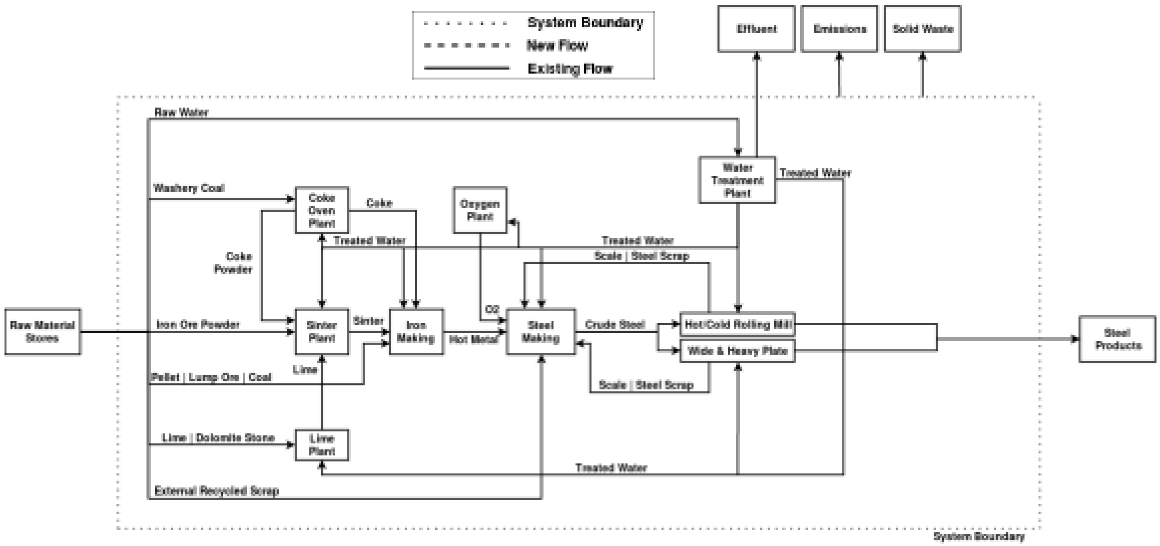


Figure 7 - Historical Integrated Steel Making Process

Due to the complexity of the steel manufacturing process and the diversity of industry size and configurations, only major flows are considered. This approach allows for a comparison to be drawn across time to current day processes, while also accurately reflecting the system historically. This also allows for the resolution of the model to be consistent over time, which is important for metric comparison of systems in ecological network analysis. The structure and flow matrix is presented in A.2 Historical Structure and Flow Matrix Construction.

The flows for the historical analysis are represented in Table 1 below.

Table 1 - Historical Flow Values Used in Model

Flow From	Flow To	Value	Units	Historical Source
Washery Coal	Coking Plant	1.4450	ton/ton-cs	CISY 1989
Water	Coking Plant	4.4834	ton/ton-cs	**
Hot Rolled Sheet	Cold Rolling Plant	0.0500	ton/ton-cs	CISY 1989
Water	Cold Rolling Plant	0.1494	ton/ton-cs	**
Basic Oxygen Furnace Slag	Construction Material Plant	0.0085	ton/ton-cs	Yin 2009
Water	Entire	21.5000	ton/ton-cs	CISY 1998
Flume Emissions	Environment	1.2000	ton/ton-cs	Price et al. 2001 for year 1988
Dust Emissions	Environment	0.0017	ton/ton-cs	***
SO2 Emissions	Environment	0.0024	ton/ton-cs	***
NOx Emissions	Environment	0.0033	ton/ton-cs	***
Effluent	Environment	2.2081	ton/ton-cs	CISY 1989
Con. Cast Slab	Hot Rolling Plant	0.3464	ton/ton-cs	CISY 1989
Water	Hot Rolling Plant	4.8263	ton/ton-cs	**
Lump Ore	Iron Plant	1.7920	ton/ton-cs	CISY 1989
Coal	Iron Plant	0.5890	ton/ton-cs	CISY 1989
Sinter Ore	Iron Plant	1.6020	ton/ton-cs	Sun et al 2013 for year 1990
Coke	Iron Plant	0.6320	ton/ton-cs	Sun et al 2013 for year 1990
Water	Iron Plant	3.5076	ton/ton-cs	**
Wide & Heavy Plate Products	Market	0.6927	ton/ton-cs	CISY 1989
Cold Rolling Products	Market	0.2131	ton/ton-cs	CISY 1989
Hot Rolled Plate Products	Market	1.4762	ton/ton-cs	CISY 1989
Cold Rolling Scrap/Scale	Scrap/Scale	0.0080	ton/ton-cs	CISY 1988
Hot Rolling Scrap/Scale	Scrap/Scale	0.0556	ton/ton-cs	CISY 1989
Wide & Heavy Plate Scrap/Scale	Scrap/Scale	0.0176	ton/ton-cs	CISY 1989
Lime Plant	Sinter Plant	0.0635	ton/ton-cs	
Iron Ore Powder	Sinter Plant	1.1538	ton/ton-cs	
Lime (Raw Material Yard)	Sinter Plant	0.0346	ton/ton-cs	
Coke Powder	Sinter Plant	0.0680	ton/ton-cs	CISY 1989
Water	Sinter Plant	0.4835	ton/ton-cs	**
Lime & Dolomite	Steel Plant	0.0000	ton/ton-cs	Rosst and Feng 1990

Table 1 - Historical Flow Values Used in Model (Continued)

Oxygen	Steel Plant	0.0530	tce/ton-cs	*Est based on US Prod
Hot Liquid Iron	Steel Plant	1.0000	ton/ton-cs	CISY 1989
Scrap/Scale	Steel Plant	0.0950	ton/ton-cs	CISY 1989
Water	Steel Plant	0.5978	ton/ton-cs	**
Crude Steel	To Plate, HR, CR, and Construction	0.5589	ton/ton-cs	Sun et al 2013 for year 1990
Effluent	Water Treatment Plant	0.1250	ton/ton-cs	-
Con. Cast Heavy Slab	Wide & Heavy Plate Plant	0.1625	ton/ton-cs	CISY 1989
Water	Wide & Heavy Plate Plant	4.8263	ton/ton-cs	**
* = Estimate **Using Ratio's from Current Time and Assuming 210m^3/ton crude steel *** Using 2x the current values as estimate				

3.1.3 Current Model Data Acquisition and Assumptions

The data for the simplified current day model structure and flow data was provided by industry partners within the CSI. The assumptions for the current model are as follows:

- The co-location of industries that could benefit from the products or waste streams of this historical plant are outside of the historical system boundaries
- Due to the steel manufacturing fuel use being represented largely by coal, a conversion of off-gasses into coal equivalent is assumed

- Byproduct gasses irregularities in generation are negligible. Uncertainty factors such as equipment maintenance could affect the stable production of gasses.

3.1.4 Current Model Structure and Flow Construction

The simplified current day structure of the steel manufacturing process is represented in Figure 8.

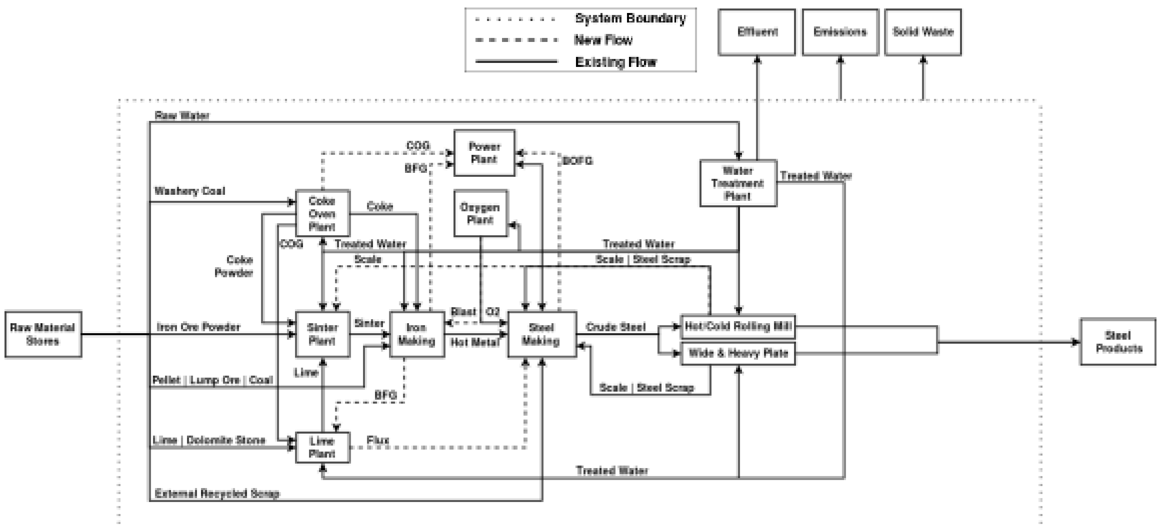


Figure 8 - Current Steel Manufacturing Process

As demonstrated in Figure 7, the major changes from our historical model are the additions of waste-gas energy recovery systems, increased intra-plant recycling, and the optimization of material flows. These structure and flow changes are represented in Table 2.

Table 2 – Present Day Values Used in Model

Flow From	Flow To	Value	Units
Washery Coal	Coking Plant	0.6173	ton/ton-cs
Water	Coking Plant	0.8592	ton/ton-cs
Hot Rolled Sheet	Cold Rolling Plant	0.2096	ton/ton-cs

Table 2 – Present Day Values Used in Model (Continued)

Water	Cold Rolling Plant	0.0286	ton/ton-cs
Water	Entire	4.1200	ton/ton-cs
Flume Emissions	Environment	0.0003	ton/ton-cs
Dust Emissions	Environment	0.0009	ton/ton-cs
SO2 Emissions	Environment	0.0012	ton/ton-cs
NOx Emissions	Environment	0.0016	ton/ton-cs
Effluent	Environment	0.1300	ton/ton-cs
Con. Cast Slab	Hot Rolling Plant	0.7096	ton/ton-cs
Water	Hot Rolling Plant	0.9249	ton/ton-cs
Pellett	Iron Plant	0.3904	ton/ton-cs
Lump Ore	Iron Plant	0.0981	ton/ton-cs
Coal	Iron Plant	0.2019	ton/ton-cs
Sinter Ore	Iron Plant	1.2365	ton/ton-cs
Coke	Iron Plant	0.3173	ton/ton-cs
Oxygen Blast	Iron Plant	0.0012	tce/ton-cs
Water	Iron Plant	0.6722	ton/ton-cs
Lime & Dolomite Stone	Lime Plant	0.2942	ton/ton-cs
BFG	Lime Plant	0.0067	tce/ton-cs
COG	Lime Plant	0.0076	tce/ton-cs
Wide & Heavy Plate Products	Market	0.2692	ton/ton-cs
Cold Rolling Products	Market	0.1923	ton/ton-cs
Hot Rolled Plate Products	Market	0.4827	ton/ton-cs
COG	Outside Park Power Plant	0.0036	tce/ton-cs
BFG	Power Plant	0.0477	tce/ton-cs
BOFG	Power Plant	0.0289	tce/ton-cs
COG	Power Plant	0.0013	tce/ton-cs
Water	Power Plant	0.2510	ton/ton-cs
Cold Rolling Scrap/Scale	Scrap/Scale	0.0173	ton/ton-cs
Hot Rolling Scrap/Scale	Scrap/Scale	0.0173	ton/ton-cs
Wide & Heavy Plate Scrap/Scale	Scrap/Scale	0.0212	ton/ton-cs
Lime Plant	Sinter Plant	0.0635	ton/ton-cs
Iron Ore Powder	Sinter Plant	1.1538	ton/ton-cs
Lime (Raw Material Yard)	Sinter Plant	0.0346	ton/ton-cs
Anthracite	Sinter Plant	0.0025	ton/ton-cs
Coke Powder	Sinter Plant	0.0538	ton/ton-cs
Scrap/Scale	Sinter Plant	0.0154	ton/ton-cs
Water	Sinter Plant	0.0927	ton/ton-cs
Lime & Dolomite	Steel Plant	0.0808	ton/ton-cs

Table 2 – Present Day Values Used in Model (Continued)

Oxygen	Steel Plant	0.0260	tce/ton-cs
Hot Liquid Iron	Steel Plant	1.0096	ton/ton-cs
Scrap/Scale	Steel Plant	0.0962	ton/ton-cs
Water	Steel Plant	0.1146	ton/ton-cs
Crude Steel	To Plate, HR, CR, and Construction	1.0000	ton/ton-cs
Effluent	Water Treatment Plant	0.1250	ton/ton-cs
Con. Cast Heavy Slab	Wide & Heavy Plate Plant	0.2904	ton/ton-cs
Water	Wide & Heavy Plate Plant	0.9249	ton/ton-cs
*** = Estimate**			

3.1.5 Summary of Plant Scale Analysis

Two configurations were analysed and discussed in the plant scale analysis. A historical perspective and current day perspective were modelled in order to demonstrate the progress of steel manufacturing over time from an ecological perspective. Data was acquired from sources throughout literature and from industry partners, and assumptions for each of the model configurations were presented. The ecological results demonstrate an increase in efficiency over time.

3.2 Eco-Industrial Park Model Construction

3.2.1 Eco-Industrial Park Model Data Acquisition

Current projects in the CSI are underway to substantiate the sustainability and efficiency claims through EIP design by Anshan Steel Company. This company is building the Bayuquan Eco-Industrial Park. Through currently still under construction, the goal is to utilize the waste streams as well as the products produced by the steel mill within the park.

3.2.2 Eco-Industrial Park Model Assumptions

The data for the EIP model structure and flow data was provided by industry partners within the CSI. The assumptions for the current model are as follows

- Future steel manufacturing will continue to use the BOF process
- Due to the steel manufacturing fuel use being represented largely by coal, a conversion of off-gasses into coal equivalent is assumed
- Byproduct gasses irregularities in generation are negligible which in reality, uncertainty factors such as equipment maintenance could affect the stable production of gasses.

3.2.3 Eco-Industrial Park Model Structure

The structure of the EIP model used in our analysis is reflected below in Figure 9.

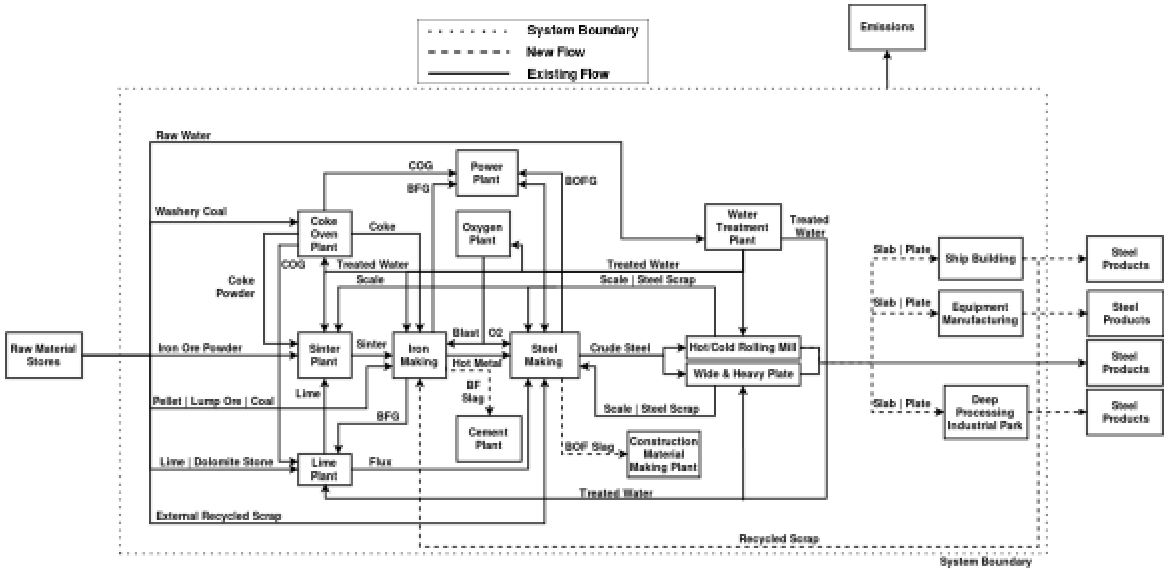


Figure 9 - EIP Configuration

The major additions from the current model is the co-location of the construction material making plant and the cement plant for using the excess BF and BOF slags, and the use of recycled scraps from the ship building, equipment manufacturing, and deep processing industries.

3.2.4 Eco-Industrial Park Model Flow

Table 3 introduces the EIP flow values used in the EIP model analysis.

Table 3 - Eco-Industrial Park Values Used in Model

Flow From	Flow To	Value	Units
Blast Furnace Slag	Cement Plant	0.3481	ton/ton-cs
Washery Coal	Coking Plant	0.6173	ton/ton-cs
Water	Coking Plant	0.8592	ton/ton-cs
Hot Rolled Sheet	Cold Rolling Plant	0.2096	ton/ton-cs
Water	Cold Rolling Plant	0.0286	ton/ton-cs
Basic Oxygen Furnace Slag	Construction Material Plant	0.1250	ton/ton-cs

Table 3 – Eco-Industrial Park Values Used in Model (Continued)

Slab & Plate	Deep Processing Industrial Park *	0.3846	ton/ton-cs
Water	Entire	4.1200	ton/ton-cs
Flume Emissions	Environment	0.0003	ton/ton-cs
Dust Emissions	Environment	0.0009	ton/ton-cs
SO2 Emissions	Environment	0.0012	ton/ton-cs
NOx Emissions	Environment	0.0016	ton/ton-cs
Effluent	Environment	0.1300	ton/ton-cs
Slab & Plate	Equipment Manufacturing *	0.1442	ton/ton-cs
Con. Cast Slab	Hot Rolling Plant	0.7096	ton/ton-cs
Water	Hot Rolling Plant	0.9249	ton/ton-cs
Pellett	Iron Plant	0.3904	ton/ton-cs
Lump Ore	Iron Plant	0.0981	ton/ton-cs
Coal	Iron Plant	0.2019	ton/ton-cs
Sinter Ore	Iron Plant	1.2365	ton/ton-cs
Coke	Iron Plant	0.3173	ton/ton-cs
Oxygen Blast	Iron Plant	0.0012	tce/ton-cs
Water	Iron Plant	0.6722	ton/ton-cs
Lime & Dolomite Stone	Lime Plant	0.2942	ton/ton-cs
BFG	Lime Plant	0.0067	tce/ton-cs
COG	Lime Plant	0.0076	tce/ton-cs
Wide & Heavy Plate Products	Market	0.2692	ton/ton-cs
Cold Rolling Products	Market	0.1923	ton/ton-cs
Hot Rolled Plate Products	Market	0.4827	ton/ton-cs
COG	Outside Park Power Plant	0.0036	tce/ton-cs
BFG	Power Plant	0.0477	tce/ton-cs
BOFG	Power Plant	0.0289	tce/ton-cs
COG	Power Plant	0.0013	tce/ton-cs
Water	Power Plant	0.2510	ton/ton-cs
Cold Rolling Scrap/Scale	Scrap/Scale	0.0173	ton/ton-cs
Hot Rolling Scrap/Scale	Scrap/Scale	0.0173	ton/ton-cs
Wide & Heavy Plate Scrap/Scale	Scrap/Scale	0.0212	ton/ton-cs
Slab & Plate	Ship Building *	0.0135	ton/ton-cs
Lime Plant	Sinter Plant	0.0635	ton/ton-cs
Iron Ore Powder	Sinter Plant	1.1538	ton/ton-cs
Lime (Raw Material Yard)	Sinter Plant	0.0346	ton/ton-cs
Anthracite	Sinter Plant	0.0025	ton/ton-cs
Coke Powder	Sinter Plant	0.0538	ton/ton-cs

Table 3 – Eco-Industrial Park Values Used in Model (Continued)

Scrap/Scale	Sinter Plant	0.0154	ton/ton-cs
Water	Sinter Plant	0.0927	ton/ton-cs
Lime & Dolomite	Steel Plant	0.0808	ton/ton-cs
Oxygen	Steel Plant	0.0260	tce/ton-cs
Hot Liquid Iron	Steel Plant	1.0096	ton/ton-cs
Scrap/Scale	Steel Plant	0.0962	ton/ton-cs
Water	Steel Plant	0.1146	ton/ton-cs
Crude Steel	To Plate, HR, CR, and Construction	1.0000	ton/ton-cs
Effluent	Water Treatment Plant	0.1250	ton/ton-cs
Con. Cast Heavy Slab	Wide & Heavy Plate Plant	0.2904	ton/ton-cs
Water	Wide & Heavy Plate Plant	0.9249	ton/ton-cs
*** = Estimate from Industry Partners**			

3.3 Eco-Industrial Park Expansion

3.3.1 Key Functional Role Identification and Implementation

The research from Layton et al. (2017) demonstrates the effectiveness of implementing a decomposer role, specifically agriculture, within EIPs and how detritivores can improve efficiencies throughout the industrial network. In the Bayuquan EIP analyzed previously, there is no such role. However, using the dependence on water characterized in the product life cycle introduced by Bras (1997) and the heavy dependence on water found throughout the previous models, actors that treat water yet mimic the decomposer role were investigated as a potential addition that would result in increased efficiency and environmental sustainability of the CSI. Constructed wetlands, using the processes phytoremediation and subsequent pyrolysis after their lifespan, were investigated as a to reduce the waste water treatment energy, costs, and fresh water consumption in addition to supplementing biochar into the steel making process. These additions would add two actors that mimic the detritivore's decomposing role to the EIP.

3.3.2 Constructed Wetlands to Treat Wastewater

Water in industry is often seen as a low-cost resource, and therefore is historically used in an inefficient manner. However, rising fresh water and treatment costs within industry have caused a shift in focus to water conservation efforts. Second only to iron and energy, water is the most important commodity in steel manufacturing (American Iron and Steel Institute, 1999). Mostly due to evaporation losses, efficient steel making today requires approximately 4.12 m^3/tonne of fresh water. To improve the current water network within steel manufacturing, novel treatment methods are required to reduce the amount of freshwater consumption the steel industry consumes, leading to reduced operating costs and environmental impact. Cooling water treatment accounts for approximately 97% of all treatment demand within the iron and steel industry. Therefore, reducing the amount of cooling water requiring traditional treatment and decreasing the amount of effluent generated from this process could have major impacts in the overall amount of energy and water consumption the steel manufacturing process generates. The major contaminants from this process that need treatment before recycling are chloride compounds and suspended solids. The conductivity removal is a key component of the reclamation process. Without this, the water is not suitable for processes that demand high water quality and could corrode mechanical equipment.

Constructed wetlands are investigated to improve the water quality of effluent generally discarded to the environment and determine the potential of reuse in the steel manufacturing process after treatment. Constructed wetlands require very minimal maintenance and are low cost. If the application of constructed wetlands in steel manufacturing were implemented, there would be decreases in cost, water, and energy consumption while also improving overall water quality. Constructed wetlands are now being employed to remove contaminants such as Suspended Solids (SS), Chemical Oxygen Demand (COD), Nitrogen (N), Phosphorus (P), and other pollutants in wastewater across the world. The wetland accomplishes this through processes such as filtration, absorption, and plant uptake (Phytoremediation). Phytoremediation is the ability for plants to concentrate elements and compounds from their environment and to metabolize various molecules in their tissues. Phytoremediation is one of the most economical ways to treat wastewater with some studies finding it to cost 10–1000 times less than conventional civil engineering technologies (Barcelo & Poschenrieder, 2003). After removing the contaminants from the wastewater, crop disposal of the plants includes pyrolysis, composting and compaction to reduce the volume of plant biomass, and incineration, ashing, and liquid extraction (Sas-Nowosielska et al., 2004). Some scientists are also finding potentials to use the plants as a feedstock for biofuel production, that could then be used to further decrease energy consumption in steel making (Sharma, Wungrampha, Singh, Pareek, & Sharma, 2016). The standards for effluent in the CSI are below in Table 4.

Table 4 - CSI Effluent Limits

Area of Production	Contaminant	Mg/L (Except pH)
Total Discharge of Wastewater	pH	6-9
	SS	20
	Ammonia	5

Table 4 – CSI Effluent Limits (Continued)

	Total N	15
	Total P	0.5
	Phosphorus Oil	3
	Phenol	0.5
	Cyanide	0.5
	Flouride	10
	Iron	2
	Zinc	1
	Copper	0.3
Workshop	Arsenic	0.1
	Hexevalent Chromium	0.05
	Chromium	0.1
	Lead	0.1
	Nickel	0.05
	Cadmium	0.01
	Mercury	0.01

In section 3.3.3, pyrolysis is investigated as a potential end use for the plants.

3.3.2.1 Constructed Wetlands Assumptions

The assumptions in the addition of constructed wetlands to the expanded model are as follows:

- The wetlands are in an environment suitable for the growth of plants year around. This assumption could be mitigated through the use of greenhouses to house the plants, but this would require over 80,000 m^2 of area, increasing infrastructure costs.
- The constructed wetlands are separated from the potential of overflow during climatic events, as well as leeching into the groundwater supply. This could be addressed through the use of concrete basins and substrate liners, in addition to

overflow areas surrounding the treatment area, but would again raise costs of construction.

- The major focus of the wetlands is the removal of chlorides and suspended solids due to this being the major pollutant in cooling water, and cooling water making up 97% of the total water treatment use in integrated steel manufacturing. Other contaminants are of secondary concern in this model addition until this model is refined further on a plant-scale application.
- It is assumed that there is a 10% decline in freshwater consumption and 46% decline in wastewater discharge with the addition of constructed wetlands (Malone, Bras, Weissburg, Zhang, & Zhao, 2017).

3.3.3 Pyrolysis of Wetland Plants

The replacement of fossil fuels by various renewable energy sources is one of the most important issues in sustainable development strategies (Lund, 2007). Confronting this, biomass offers advantages over fossil fuels because it is a renewable source of energy while also being CO2 neutral (Wu, Yin, Yuan, Zhou, & Zhuang, 2010). In the Constructed Wetlands to Treat Wastewater section of this thesis, the chloride removal in steel wastewater is examined as a potential solution to insert a decomposing role into traditional steel manufacturing. Pyrolysis is a solution that could be employed to provide an end use and close the loop in the steel manufacturing process, while effectively introducing another detritivore into the steel manufacturing ecosystem.

In steel manufacturing, literature suggests the research conducted on the substitution of fossil reducing agents has focused on the blast furnace where biomass and charcoal could replace a portion of the coal in coke production or pulverized coal (Babich, Senk, & Fernandez, 2010; MacPhee, Gransden, Giroux, & Price, 2009; J. G. Mathieson, Rogers, Somerville, & Jahanshahi, 2012). In coke production, literature suggests the coal-charcoal blend could be around 5% without degradation of the coke quality (MacPhee et al., 2009). Additionally, charcoal could replace the re-carburizer carbon in the basic oxygen furnace (J. Mathieson, Rojers, Somerville, Ridgeway, & Jahanshahi, 2011).

At a minimum, raw biomass must be torrefied before injection into the blast furnace (W.-H. Chen, Du, Tsai, & Wang, 2012). However, pyrolysis of raw biomass leads to increased energy density of the product. Pyrolysis is the thermal decomposition of biomass into heterogenous gaseous, liquid, and solid intermediates in an endothermic reaction. The liquid product is a mixture with characteristics such as high alkalinity and oxygen content, which can be further refined into fuels. The solid product, also known as char, can be used as a fuel or soil amendment (Babu, 2008). Various pyrolysis techniques have been developed ranging from ancient earth pits to modern continuous type screw reactors. Modern pyrolysis techniques typically achieve anywhere from 25-35% yield, with slow pyrolysis with wood yields around the same (Antal & Grønli, 2003; Duku, Gu, & Hagan, 2011; Lovel, Vining, & Dell 'amico, 2009). In slow pyrolysis, biomass is pyrolyzed at slow heating rates, which results in increased char formation. Slow pyrolysis has a residence time ranging from minutes to days whereas regular pyrolysis has a residence time on the order of seconds to minutes. The properties of charcoal are comparable or better than the pulverized fossil coal used as a fossil reducing agent in the blast furnace (Babich et al., 2010; Jenkins, Baxter, Miles, & Miles, 1998; J. Mathieson et al., 2011; J. G. Mathieson et al., 2012). In addition to decreased CO2 emissions, the use of charcoal in the blast furnace has the capacity to reduce the amount of fluxes such as limestone and BOF slag due to the basic ash chemistry. This would result in lower slag amounts, possibly leading to increased productivity within the blast furnace (Babich et al., 2010).

3.3.3.1 Pyrolysis Assumptions

The elements Na, K, Mg, Ca, S, Si and Cl are the most problematic mineral and elemental ions that plants accumulate that can interfere in thermochemical processes such as pyrolysis and are abundant in the plants designed for the constructed wetlands (Miles et al., 1996). However, the inorganic fuel elements Na, K, Mg, Ca, S, and Si are nearly completely contained in the ash and thus are easily disposed. However, the Cl in biomass can be a significant problem because it interacts with any vaporized metals, forming sulphates on the boiler surfaces (Allison, Robbins, Carli, Clifton-Brown, & Donnison, 2010). In addition, Cl can also lead to hydrochloric acid and dioxin emissions (Lewandowski & Kicherer, 1997). Hydrochloric acid is the third most important pollutant to global acidification after SO_2 and NO_x therefore the treatment of this by-product is of utmost importance. In the pyrolysis process, as volatile gasses combine, they often form corrosive deposits that can degrade components of the boiler.

Therefore, it is assumed the high feedstock mineral content can be mitigated by using newer alloys in the components of the pyrolysis system that can minimize and withstand the corrosion and also by controlling the temperature of the reaction. To mitigate the dioxin and hydrochloric acid emissions, charcoal filters for dioxin removal combined with dry scrubbing technologies have had many successful applications that could be employed. For example, bicarbonate has a high reactivity as a neutralizing agent for acid gasses such as HCl (Fellows & Pilat, 1990) and has been used in a number of waste-to-energy plants in Europe and Asia (Vehlow, 2015). The residues produced during this process can then be used as a feedstock in chemical companies for sodium carbonate production, though this flow is assumed to be neglected in this model. Further studies should investigate the amount produced, and how other industries could benefit from the bicarbonate production.

It is also assumed the ratio of biochar generated from pyrolysis using CO_2 has more weight loss than traditional pyrolysis with N_2 due to the reaction of the CO_2 purge gas with the fixed carbon contained within the biomass. The exact amount is dependent on the biomasses present. The hemicellulose, cellulose, and lignin in the biomass are the main constituents that affect the amount of char generated in pyrolysis. According to Eseltine (2011), and assuming *Sorghum* is similar to the types of plants used in the models constructed wetlands and temperature of the BF flue gas of 400-600˚C as purge gas, only 38% of the biomass' dry weight is converted to biochar. Assuming an 8 week grow cycle before trimming, over 89,988 kg of dried biomass is accumulated. When converting this to char, the amount generated per day is around 610 kg. Adding this char into the steel manufacturing process reduces the amount of coal used in the blast furnace by 0.021% and the total power consumed from the steel manufacturing process by 0.198%. The power is decreased due to the higher heating value (HHV) in the product gasses due the Boudouard reaction, reaching almost 36% of the HHV of natural gas (W. Chen, Thanapal, Annamalai, Ansley, & Mirik, 2013).

Using a CO2/O2 mixture for gasification produced a gas with a much higher HHV because of the Boudouard reaction taking place under the CO2-rich conditions in the reactor. Because CO_2 separation technology has been developed, the removal of CO_2 from the product gas mixture in CO_2/O_2 gasification will increase the HHV of the product gases, and the HHV can reach almost 36% of the HHV of natural gas. (4) The optimum gasification conditions for gasifying mesquite to obtain a gas with a higher HHV would be to use an ER of 2.7 with a CO_2/O_2 mixture as the gasification medium and blending coal with the biomass to increase the percentage of fixed carbon in the fuel.

3.3.4 Eco-Industrial Park Expansion Effects on Original Model Due to Structure

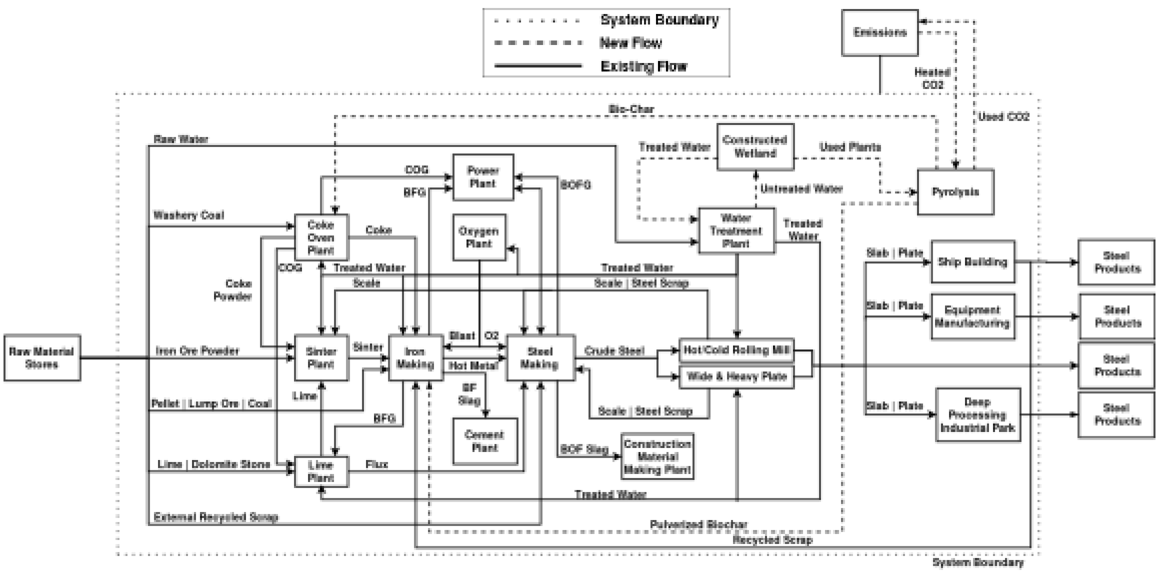


Figure 10 - Future EIP Configuration with Detritivore Actors

3.3.5 Expanded EIP Flow Model Data

Introduces the changes of material flows used in the expanded EIP model.

Table 5 - Flows for Expanded EIP Model

Flow From	**Flow To**	**Amount**	**Units**
Blast Furnace Slag	Cement Plant	0.3481	ton/ton-cs
Washery Coal	Coking Plant	0.6173	ton/ton-cs
Water	Coking Plant	0.8592	ton/ton-cs
Hot Rolled Sheet	Cold Rolling Plant	0.2096	ton/ton-cs
Water	Cold Rolling Plant	0.0286	ton/ton-cs
Basic Oxygen Furnace Slag	Construction Material Plant	0.1250	ton/ton-cs
Slab & Plate	Deep Processing Industrial Park *	0.3846	ton/ton-cs
Power Grid	Entire	0.0696	tce/ton-cs
Water	Entire	3.7080	ton/ton-cs
Flume Emissions	Environment	0.0003	ton/ton-cs
Dust Emissions	Environment	0.0009	ton/ton-cs
SO2 Emissions	Environment	0.0012	ton/ton-cs
NOx Emissions	Environment	0.0016	ton/ton-cs
Effluent	Environment	0.1300	ton/ton-cs
Slab & Plate	Equipment Manufacturing *	0.1442	ton/ton-cs
Con. Cast Slab	Hot Rolling Plant	0.7096	ton/ton-cs
Water	Hot Rolling Plant	0.9249	ton/ton-cs
Pellett	Iron Plant	0.3904	ton/ton-cs
Lump Ore	Iron Plant	0.0981	ton/ton-cs
Coal	Iron Plant	0.1977	ton/ton-cs
Sinter Ore	Iron Plant	1.2365	ton/ton-cs
Coke	Iron Plant	0.3173	ton/ton-cs
Oxygen Blast	Iron Plant	0.0012	tce/ton-cs
Water	Iron Plant	0.6722	ton/ton-cs
Lime & Dolomite Stone	Lime Plant	0.2942	ton/ton-cs
BFG	Lime Plant	0.0067	tce/ton-cs
COG	Lime Plant	0.0076	tce/ton-cs
Coke and Other Byproducts	Market	0.0346	ton/ton-cs
Wide & Heavy Plate Products	Market	0.2692	ton/ton-cs
Cold Rolling Products	Market	0.1923	ton/ton-cs
Hot Rolled Plate Products	Market	0.4827	ton/ton-cs
COG	Outside Park Power Plant	0.0036	tce/ton-cs
BFG	Power Plant	0.0477	tce/ton-cs
BOFG	Power Plant	0.0289	tce/ton-cs
COG	Power Plant	0.0013	tce/ton-cs
Water	Power Plant	0.2510	ton/ton-cs
Cold Rolling Scrap/Scale	Scrap/Scale	0.0173	ton/ton-cs
Hot Rolling Scrap/Scale	Scrap/Scale	0.0173	ton/ton-cs
Wide & Heavy Plate Scrap/Scale	Scrap/Scale	0.0212	ton/ton-cs
Slab & Plate	Ship Building *	0.0135	ton/ton-cs
Lime Plant	Sinter Plant	0.0635	ton/ton-cs
Iron Ore Powder	Sinter Plant	1.1538	ton/ton-cs

Table 5 – Flows for Expanded EIP Model (Continued)

Lime (Raw Material Yard)	Sinter Plant	0.0346	ton/ton-cs
Anthracite	Sinter Plant	0.0025	ton/ton-cs
Coke Powder	Sinter Plant	0.0538	ton/ton-cs
Scrap/Scale	Sinter Plant	0.0154	ton/ton-cs
Water	Sinter Plant	0.0927	ton/ton-cs
Lime & Dolomite	Steel Plant	0.0808	ton/ton-cs
Oxygen	Steel Plant	0.0260	tce/ton-cs
Hot Liquid Iron	Steel Plant	1.0096	ton/ton-cs
Scrap/Scale	Steel Plant	0.0962	ton/ton-cs
Water	Steel Plant	0.1146	ton/ton-cs
Crude Steel	To Plate, HR, CR, and Construction	1.0000	ton/ton-cs
Effluent	Water Treatment Plant	0.0675	ton/ton-cs
Con. Cast Heavy Slab	Wide & Heavy Plate Plant	0.2904	ton/ton-cs
Water	Wide & Heavy Plate Plant	0.9249	ton/ton-cs
Wetlands	Entire	0.5559	ton/ton-cs
Pyrolysis	Iron Plant	0.0042	ton/ton-cs
Wetlands	Pyrolysis	0.0000	ton/ton-cs
Pyrolysis	Power Plant	0.0013	ton/ton-cs
* = Estimate from Industry Partners			

CHAPTER 4. SYSTEM ANALYSIS RESULTS

4.1 Steel Industry Results: Plant Scale

4.1.1 Historical

Table 6 introduces the calculated ecological structure statistics for the historical configuration of the steel manufacturing process.

Table 6 - Historical Structure Statistics

λ_{max}	LD	P_R	G	V	N	L	N_{Pred}	N_{Prey}	C
1.4422	0.95	1.25	2.375	1.9	20	19	8	10	0.0475

Table 7 introduced the ecological flow-based statistics for the historical steel manufacturing configuration.

Table 7 - Historical Flow Statistics

FCI	MPL	AMI	ASC	DC	TSO	TST_P	ASC/DC	R
0.0003	1.8965	1.2738	99.4314	297.092	197.661	51.109	0.334681	0.5285

Figure 11 demonstrates the past configurations place on the robustness versus efficiency curve.

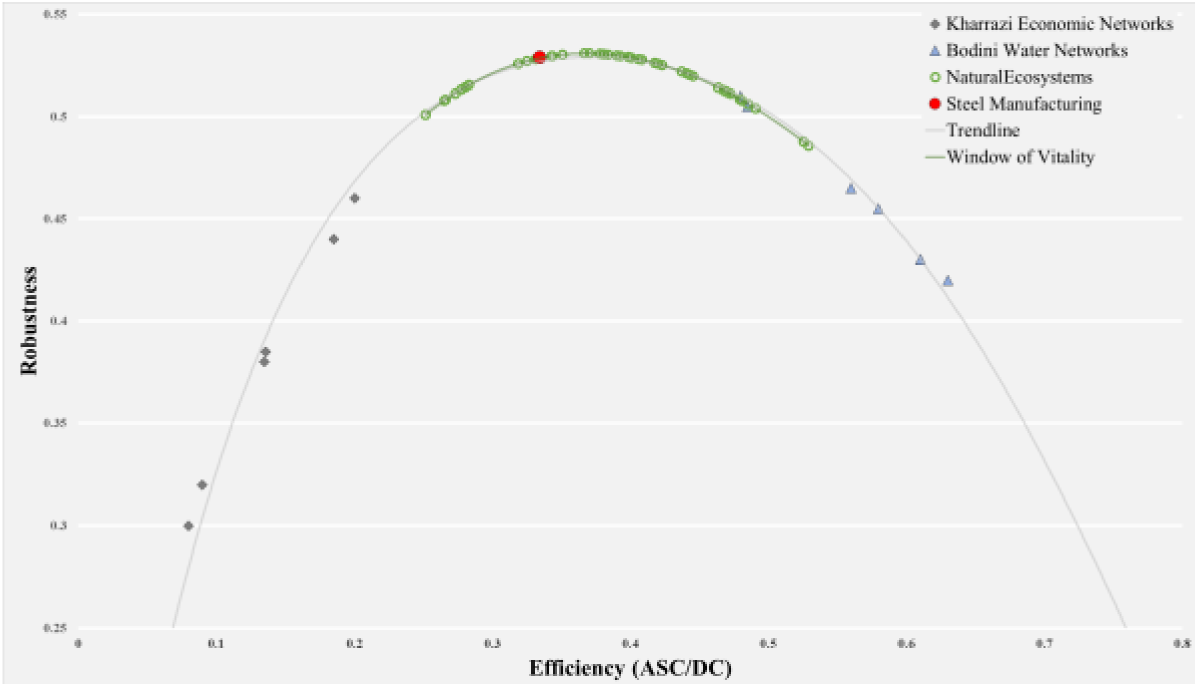


Figure 11 - Efficiency vs. Robustness for Historical Steel Manufacturing Configuration

4.1.2 Current Day

Table 8 introduces the calculated ecological structure statistics for the present-day steel manufacturing configuration.

Table 8 - Present Day Structure Statistics

λ_{max}	LD	P_R	G	V	N	L	N_{Pred}	N_{Prey}	C
2.155176	1.7	1	2.615384615	2.615384615	20	34	13	13	0.085

Table 9 lists the ecological flow statistics for the present-day steel manufacturing configuration.

Table 9 - Present Day Flow Statistics

FCI	MPL	AMI	ASC	DC	TSO	TST_P	ASC/DC	R
0.0161	2.0646	1.4611	30.4730	92.5777	62.1047	14.050	0.329161	0.5276

Figure 12 demonstrates the present-day configurations place on the robustness curve. The steel manufacturing data point representing the present-day configuration is progressing upwards on the curve when compared to the past configuration.

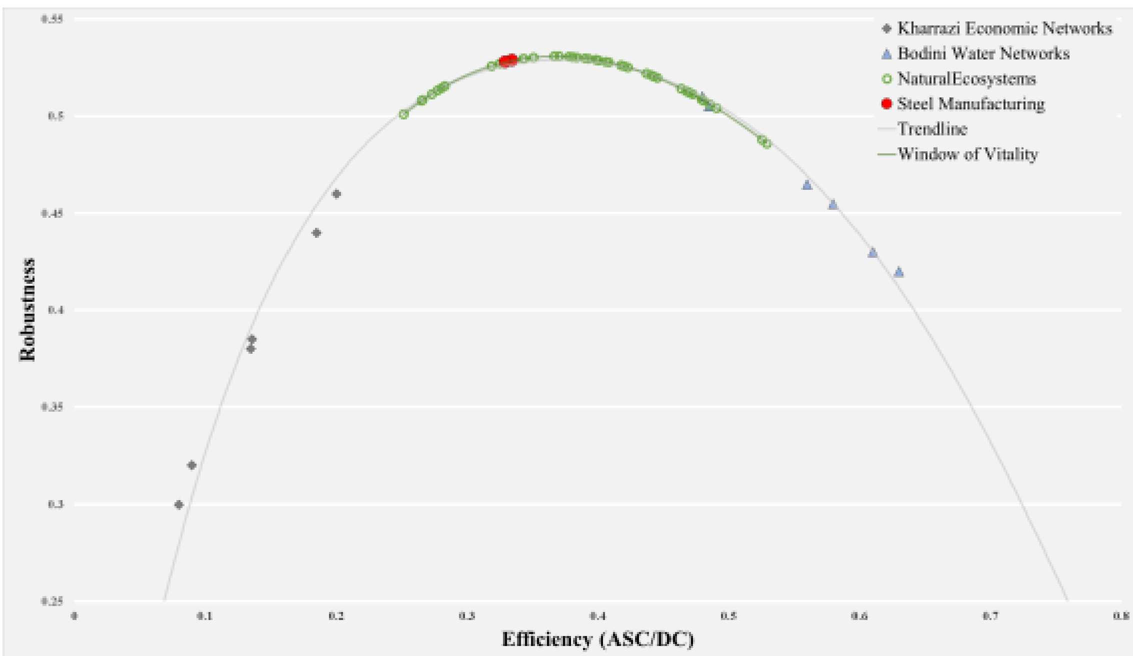


Figure 12 - Efficiency vs. Robustness for Present Day Steel Manufacturing Configuration

4.2 Eco-Industrial Park Results

4.2.1 Eco-Industrial Park

Table 10 lists the results of the ecological structure statistics for the EIP steel manufacturing network.

Table 10 - EIP Structure Statistics

λ_{max}	LD	P_R	G	V	N	L	N_{Pred}	N_{Prey}	C
2.11124	1.9	0.722222222	2.111111111	2.923076923	20	38	18	13	0.095

Table 11 lists the results of the ecological flow statistics for the EIP steel manufacturing process.

Table 11 - EIP Flow Statistics

FCI	MPL	AMI	ASC	DC	TSO	TST_P	ASC/	R
0.0143	2.1623	1.6679	35.984	99.622	63.638	14.752	0.3612	0.5306

Figure 13 demonstrates the EIP configurations place on the robustness curve. The data point representing the EIP configuration traversed into the window of vitality when compared to the present day and historical configurations.

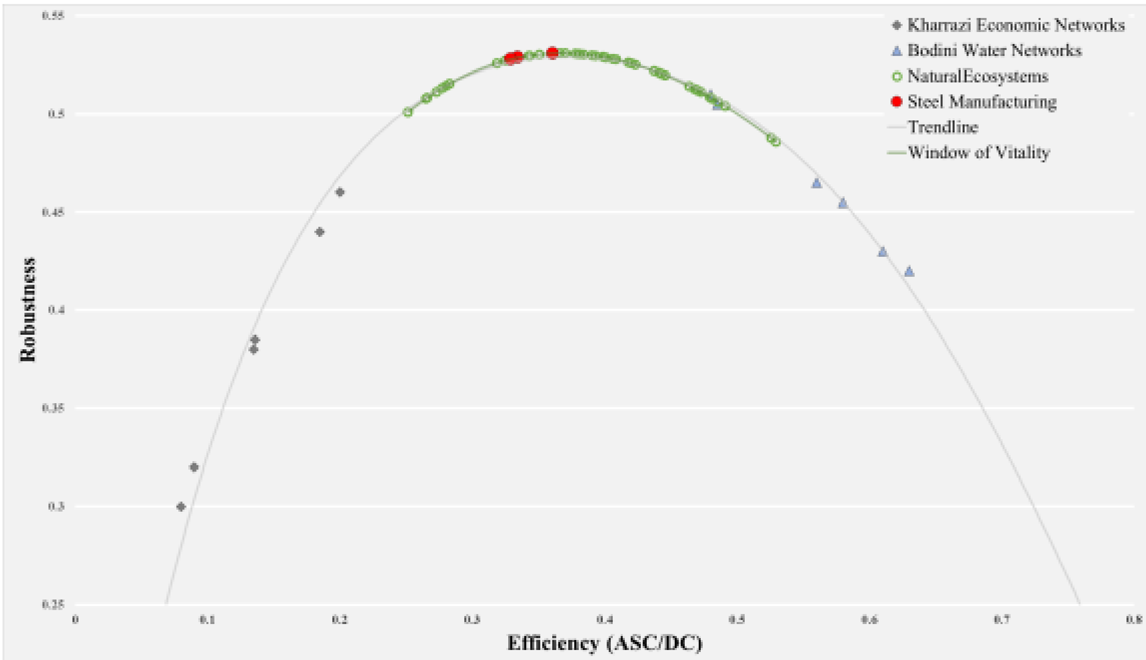


Figure 13 - Efficiency vs. Robustness for the EIP Steel Manufacturing Configuration

4.2.2 Discussion of Historical, Current, and Eco-Industrial Park Results

The results in when comparing Table 7 to Table 9 show the system has improved substantially from the past to present in *FCI*, *MPL*, and *AMI* flow statistics. In natural systems, an increase of *FCI* represents a system-wide decrease in dependence on external resources by an increase in recycling within the system. This decrease results in a lower reliance on external scrap in steel manufacturing. Further, an increased *AMI* is indicative of increased system maturity and cycling within the ecosystem (Odum, 1969).

Complementing these values is TST_p, indicating an increase in process efficiency through its decreasing value. This decrease in TST_p most likely is due to the overall decrease in waste within the steel industry. Our results also suggest slight increase in *R*, with a corresponding increase in alpha, or *ASC/DC*. These results suggest the progression of the CSI is indicative of a system that is decreasing redundancy by increasing efficiency.

Our addition of the steel industry contributes to the analysis by Layton et al. (2016) in demonstrating the progression of steel manufacturing through time. As demonstrated by our results in Figure 11, Figure 12, and Figure 13, the steel industry is moving towards greater balance between redundancy and efficiency to better mimic how natural ecosystems organize themselves. However, our results also suggest that the future of steel manufacturing has potential to improve further from the current state. The incorporation of the steel manufacturing industry with sister industries could be configured as demonstrated in Figure 9. These industries may share resources or waste streams and has been shown to further reduce waste and consumption of resources while still mimicking the balance of redundancy and efficiency of natural ecosystems as observed in Figure 13. These results suggest that understanding how these industrial ecosystems interact can aid in the future design, development, and operation of sustainable industrial systems. This analysis therefore suggests that cooperative industries which are coupled to maximize efficient use of resources while also minimizing waste is a design which could further improve the overall sustainability of the CSI. Expanding upon the success demonstrated by the EIP configuration in Figure 13, section 4.3 demonstrates how this configuration could be extrapolated upon, implementing the decomposer roles highlighted in section 3.3.

4.2.3 Summary of Eco-Industrial Park Results

4.3 Eco-Industrial Park Expansion Results

Table 12 lists the calculated expanded EIP structural statistics.

Table 12 - Expanded EIP Structure Statistics

λ_{max}	LD	P_R	G	V	N	L	N_{Pred}	N_{Prey}	C
2.49008	2.5	0.75	2.5	3.333333333	20	50	20	15	0.125

Table 13 lists the results of the ecological flow-based statistics for the expanded EIP steel manufacturing process.

Table 13 - Expanded EIP Flow Statistics

FCI	MPL	AMI	ASC	DC	TSO	TST_P	ASC/D	R
0.0143	2.5149	1.8282	36.696	97.836	61.139	14.361	0.3750	0.5306

Figure 14 demonstrates where the expanded EIP configuration falls on the efficiency versus robustness curve. Though difficult to observe, there is slight movement towards the top of the curve from the EIP configuration point.

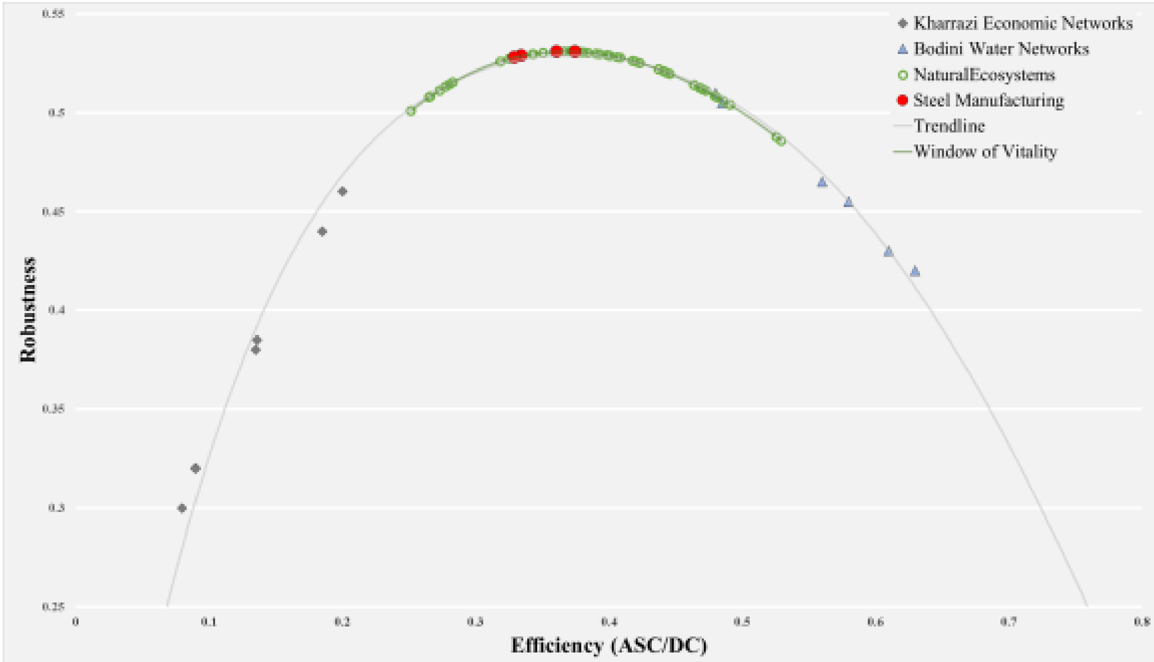


Figure 14 - Efficiency vs. Robustness for the Expanded EIP Steel Manufacturing Configuration

When comparing the EIP expansion configuration to the EIP configuration, one observes a dramatic increase of λ_{max} from 2.15 to 2.49 as expressed in Table 10 and Table 12 respectively. In natural ecosystems, the λ_{max} ranges between 2.68 and 14.17 with an average of 4.24 (Layton et al., 2016). This indicates that though our expanded EIP configuration performs better than the previous EIP configuration, much more work is to be done to measure up to the maximum potential for cycling found in natural systems.

Across the flow-based metrics listed in Table 13, there were increases in all the metrics that point to ecosystem maturity, health, robustness, and efficient use of materials. However, in the addition of wetlands and pyrolysis as observed in the structural modifications in Figure 10, and comparing the large movement upward on the efficiency versus robustness curve caused by the EIP configuration in Figure 9 and section 4.2, the expanded EIP results would be expected to have a similar increase. Due to only the slight increase observed in Figure 14, one could conclude that the further improvement in the steel industry on the robustness curve will originate from a variety of improvements. This could originate from increased cycling of symbiotic partners back into the steel manufacturing process as the example discussed in section 3.3.3, as these scenarios were excluded from our current EIP and expanded EIP models excluding scrap metal. If products are brought back into the steel manufacturing process, the maximum potential for cycling as well as other metrics should increase. For example, plastic waste generated from other industries could be used in the BF. These are scenarios that should be explored and optimized in future research.

4.4 CSI Configuration Comparison Throughout Time

Observing the progress made in structural configurations and material use through the CSI's history, it helps to view the metrics side by side to quantify changes. Table 14 below lists the structural and flow based metrics listed side by side for all configurations presented in this thesis.

Table 14 - Comparison of All Model Configurations

	Past	Current	EIP	Expanded EIP
Max Potential for Cycling	1.4422	2.1552	2.1112	2.4901
Linkage Density	0.9500	1.7000	1.9000	2.5000
Predator/Prey Ratio	1.2500	1.0000	0.7222	0.7500
Generalization	2.3750	2.6154	2.1111	2.5000
Vulnerability	1.9000	2.6154	2.9231	3.3333
Links	19.0000	34.0000	38.0000	50.0000
Number of Predators	8.0000	13.0000	18.0000	20.0000

Table 14 - Comparison of All Model Configurations (Continued)

Number of Prey	10.0000	13.0000	13.0000	15.0000
Connectance	0.0475	0.0850	0.0950	0.1250
Number of Special Prey	1.0000	4.0000	9.0000	9.0000
Fraction of Special Predators	0.1250	0.3077	0.5000	0.4500
Finn Cycling Index	0.0004	0.0162	0.0144	0.0143
Mean Path Length	1.8965	2.0646	2.1624	2.5150
Average Mutual Information	1.2738	1.4612	1.6679	1.8283
Ascendency	99.4315	30.4730	35.9845	36.6966
Developmental Capacity	297.0925	92.5777	99.6225	97.8361
Total System Overhead	197.6611	62.1047	63.6380	61.1395
Total System Through Flow	51.1093	14.0501	14.7521	14.3614
Alpha	0.3347	0.3292	0.3612	0.3751
Robustness	0.5285	0.5277	0.5307	0.5306

Of notable comparison in the structural metrics are the increases in λ_{max} and L_D and L. All of these values are high in natural systems, and one can observe how when progressing in time from the past configuration, there has been a steady increase until the expanded EIP configuration. Another interesting way to observe this data is by comparing the current, EIP, and expanded EIP configurations structure metrics to the past configuration as shown in Figure 15.

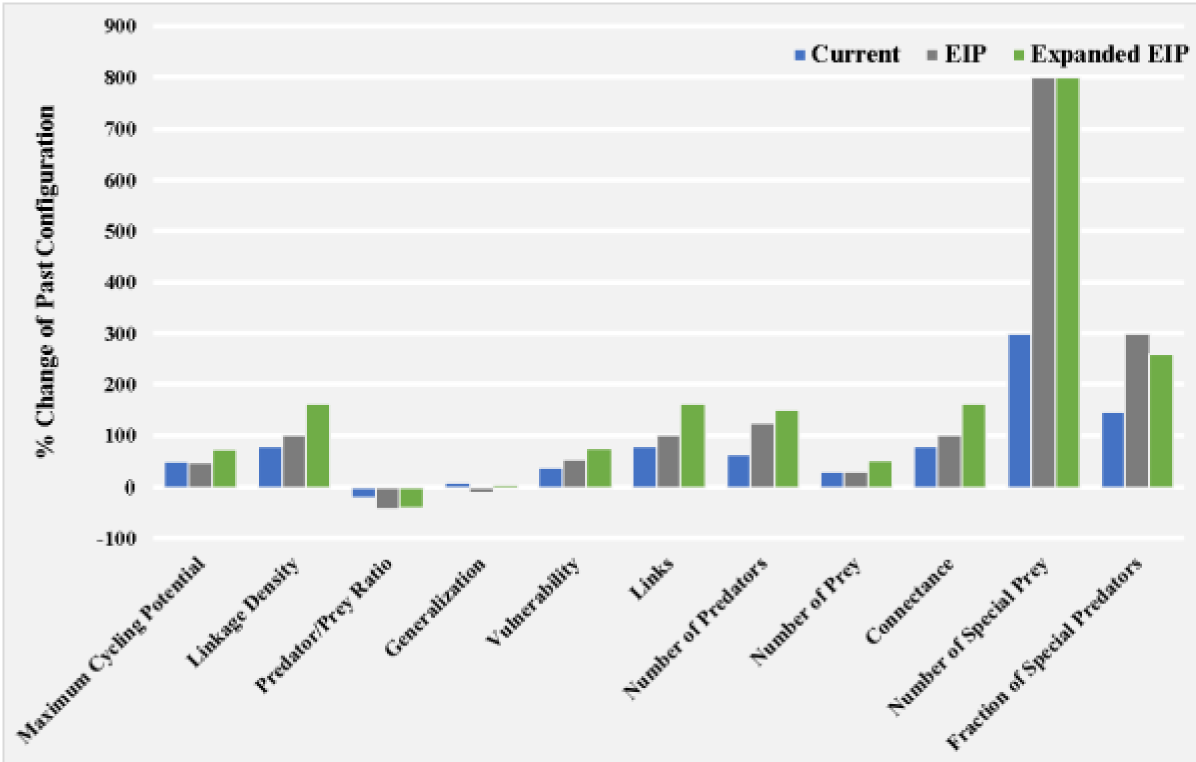


Figure 15 – Structure Metrics Comparison of All Configurations

As one might observe, there is usually a linear increase or decrease amongst the structure metrics. However, instances such as special predators and preys show a greater decrease than the expanded EIP configuration. Interestingly, this also included an increase in vulnerability in the system. This could be due to the larger fraction in the EIP of symbiotic industries that do not return any material back into the system, where in the expanded EIP with the additions of the constructed wetlands and pyrolysis, there is much more internal recycling when the ratios are performed in these structural metrics.

When analyzing the flow metrics, there is a much clear pattern of increased or decreased metrics as shown in Figure 16.

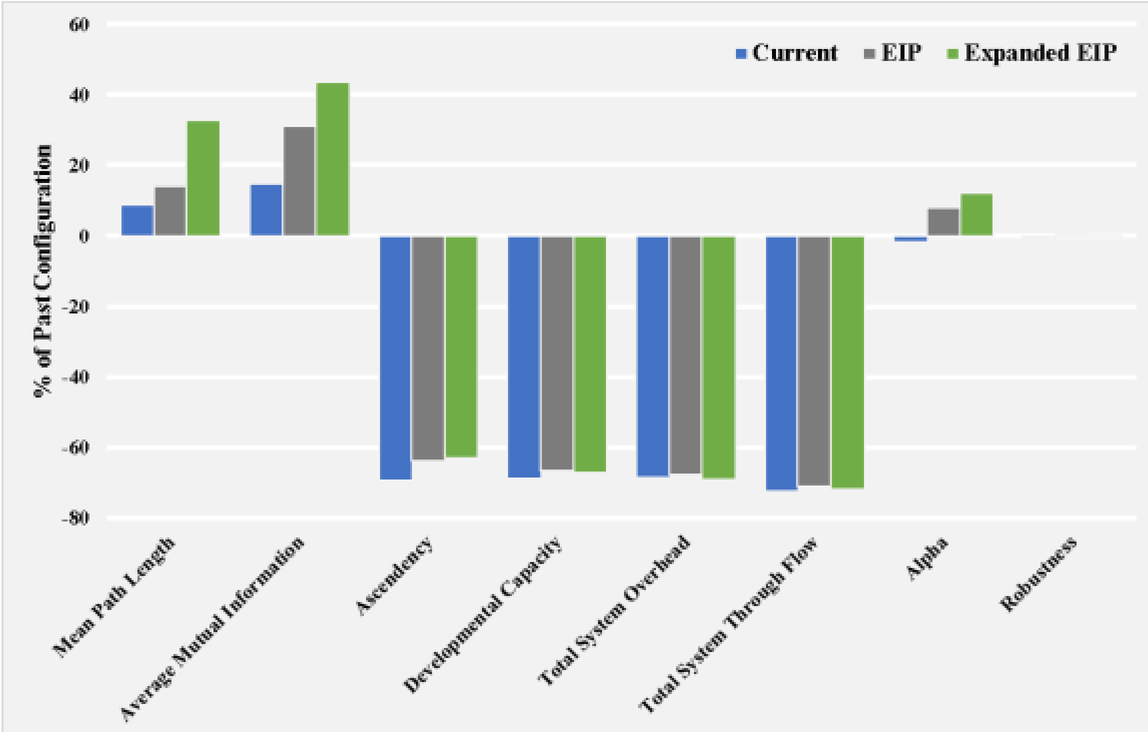


Figure 16 - Flow Metric Comparison of All Configurations

One can observe the vast increases with respect to *FCI (not pictured)* and *MPL*. These are non-dimensional metrics that allow for insight into the material flows in the different configurations. The *MPL* changes show that the current configurations allow for materials to “touch” more actors, or complexity in flow, throughout the system before being exported. In the EIP and expanded EIP configurations, the configuration becomes more streamlined. Therefore, the EIP and expanded EIP demonstrate a need for higher cycling, as their *MPL* metrics indicate that the resources used in their network are not used to their full potential. This is not to say the past configuration was of better structure, but that the EIP and expanded EIP configurations have the unrealized potential for recycling that did not exist before, as demonstrated in Figure 15’s λ_{max} metric. The results from the *FCI* are of similar result. The cycling index shows the activity throughout the system that is devoted to cycling, so these results suggest that a increasing amount of total system activity is devoting itself to cycling. The *FCI* is a dimensionless number, as is the *MPL*, that accounts for percentage of all fluxes generated by cycling, or the fraction of total activity in the system that is devoted to cycling.

The *AMI* and *MPL* both relate back to the functional prey to predator relationships. *AMI* is useful because it measures the constraints in terms of flow volumes through the different linkages. As shown in Figure 16, from the past to expanded EIP there has been a linear increase. This indicates an increase in ecosystem health and maturity, showing progress in modeling the CSI more closely to that of a biological system.

The ratio of *ASC* to *DC*, or alpha, provides a comparison in the constraints versus flexibility in the system imposed by efficiency and redundancy. We can see in Table 14 that throughout time, alpha has been increasing with a slightly decreasing robustness. This indicates a lower dependence on outside the system boundaries resources and a slightly lower ability to protect against unforeseen consequences the system might endure.

CHAPTER 5. SUMMARY AND FUTURE WORK

5.1 Summary

China produces over half of the worldwide demand of steel. Due to the magnitude of production and the associated environmental impact, this thesis investigates improvements to the Chinese steel industry through ecologically inspired systems-based modelling. This was accomplished by modelling the Chinese steel industry from a historical context until present to establish a baseline for analysis. Ecological metrics were defined and applied to the historical and current configurations in the steel industry to determine the efficacy of the Chinese steel industry when compared to natural systems. The results from this thesis indicate that historical and current improvements could be improved to measure up to the efficiency and robustness found throughout the healthiest natural ecosystems, though large efficiency improvements have been achieved through process and material optimization and improvements in controls technologies.

Next, at a higher level, the focus transitions to transforming Chinese steel manufacturing plants into eco-industrial parks by means of industrial symbiosis with other companies and calculating the associated statistical ecological metrics. Industry partners provided data to analyse a proposed EIP from an ecological perspective. Through industrial symbiosis, our results indicate that the steel industry can move into a healthier sustainable balance between efficiency and robustness that natural systems inhabit. Further, our expanded EIP results show that by utilizing functional roles found throughout nature but often are lacking in human engineered systems, there is an increase the decomposition and recycling of materials that would otherwise be discarded as waste within the CSI. This ecological perspective resulted in greater efficiencies as compared to a traditional systems perspective. In addition, when comparing the results from the varying configurations in the models, robustness of the systems increase from past configurations to the expanded EIP model, indicating a higher resiliency of the system overall.

5.2 Future Work

As mentioned throughout this thesis, the systems-level cycling of materials and energy throughout the steel industry should be investigated further. The maximum amount of cycling achieved from the expanded EIP model is still lacking when compared to performance observed in natural systems. In natural systems, over 50% of the material waste is consumed and recycled through the decomposer role. In our models of constructed wetlands and pyrolysis, the material consumption and recycling is much lower. Literature calls for an agricultural component as an excellent detritivore that is often absent in industrial systems. This is a component that has yet to be investigated that could drive the hypothesized expanded EIP further to the performance of natural systems.

In addition, the cycling of materials in EIPs needs further refinement in the model presented from our industry partners. Multiple potential symbiotic partners are not implemented throughout the EIP examined. A simple addition of a chemical industry could provide another partner that could use the by-products generated in the pyrolysis process. Further, the waste generated from some of the industries present currently in the proposed EIP do not cycle material waste back into the steel manufacturing process. As mentioned in this thesis, waste plastics from the kitchen appliance industry could be used as a supplement for the BF. These unrealized material flows and optimization of these flows are essential to match the sustainability improvements demonstrated throughout biological systems in the quest for more sustainable industrial systems.

APPENDIX A. HISTORICAL ANALYSIS SUPPLEMENTARY DATA

A.1 CSI Historical Data

The data below originates from the Steel Yearbook of 1988 (Mettalurgical Economic R&D Centre of China, 1988).

Table 15 - Steel Yearbook 1988 Data

Anshan Steel Group 1988 (Steel Statistical Yearbook 1989)						
Output (Ten Thousand Tonnes)	*Finished Rolled Steel*	*Steel Making Pig Iron*	*Blast Furnace Slag*	*Iron Ore*	*Metallurgy Coke*	
	5943	756.4	395.02	2507.22	408.55	
Energy Consumption (Ten Thousand Tonnes)	*Coking Coal*	*Fuel Coal*	*Coke*	*Electricity*	*Heavy Oil*	*Natural Gas (million m^3)*
	642.15	247.82	429.36	42.61	102.96	1.09
Fuel Consumption (Ten Thousand Tonnes)	*Sinter & Pellet*	*Iron Making*	*Steel Making and Rolling*	*Machinery Repairing and Powerplant*		
	65.67	55.89	-	100.69		
Electricity Consumption (100 million kWh)	*Mining and Mineral Processing*	*Sintering and Pelleting*	*Iron Making*	*Steel Making*	*Steel Rolling and Forging*	*Machinery Repairing and Powerplant*
	11.7	3.19	0.85	1.7	4.51	14.55

Table 5 - Steel Yearbook 1988 Data (Continued)

Process Level Statistics (Ten Thousand Tonnes)	***Coke***	**Wet Coal Consumption**	**1445**			
		Yield Ratio(%)	76.44			
	Sinter	Ratio of Good Sinter (%)	99.56			
		Fuel Consumption	68			
	Iron	Ratio of Good Pig Iron (%)	100			
		Fuel Consumption	589			
		Coal Injection	72			
		Coke	490			
		Iron Ore	1792			
	Steel	Pig Iron and Scrap	1116			
		Pig Iron	1021			
		Scrap	95			
		Alloy Additive	19.3			
		Ratio of Good Steel	10.69			
	Rolling	Ratio of Good Rolled Steel (%)	99.68			
		Equivalent Coal Consumption for Rolling	164			
		Composite Yield (%)	83.94			
	Slabbing	Yield Ratio (%)	89.16			

A.2 Historical Structure and Flow Matrix Construction

Historical Configuration			**From**																						
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Exports**	**Respiration**
To	**0**	*Imports*	0	0	1.4450	0	0	0	0	0	2.3810	0.0981	0	0	0	0	1.4407	0.0867	21.5000	0	0	0	0	0	0
	1	*Cement Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	*Coking Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4834	0	0	0	0	0	4.4834
	3	*Cold Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0500	0.1494	0	0	0	0	0.0420	0.1494
	4	*Construction Material Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	*Deep Processing Industrial Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	*Equipment Manufacturing Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	*Hot Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3464	5.2485	0	0	0	0	0.3464	5.1929
	8	*Iron Plant*	0	0	1.3770	0	0	0	0	0	0	0	0	0	0	0	1.6020	0	3.5076	0	0	0	0	0	7.8676
	9	*Lime Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0024
	10	*Grid*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11	*On-Site Power Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12	*Scrap/Scale*	0	0	0	0.0080	0	0	0	0.0556	0	0	0	0	0	0	0	0	0	0.0176	0	0	0	0	0
	13	*Ship Building Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14	*Sinter Plant*	0	0	0.0680	0	0	0	0	0	0	0.0957	0	0	0	0	0	0	0.4835	0	0	0	0	0	0.4859
	15	*Steel Plant*	0	0	0	0	0	0	0	0	1.0000	0	0	0	0.0812	0	0	0	0.5978	0	0	0	0	0	1.2068
	16	*Water Treatment Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2038
	17	*Wide & Heavy Plate Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1625	4.8260	0	0	0	0	0.1625	4.8084
	18	*Oxygen Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	19	*Wetlands*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	20	*Pyrolysis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 17 - Historical Steel Manufacturing Structure and Flow Matrix

APPENDIX B. CURRENT ANALYSIS SUPPLEMENTARY DATA

B.1 Current Structure and Flow Matrix Construction

		Current Configuration	From																					
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Exports**	**Respiration**
	0	*Imports*	0	0	0.6173	0	0	0	0	0	0.6904	0.2942	0.0709	0	0	0	1.0123	0	4.1200	0	0	0	0	0	0
	1	*Cement Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	*Coking Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6173	0	0	0	0	0	0.8510
	3	*Cold Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0562	0	0	0	0.1950	0.0286	0	0	0	0	0.1923	0.0702
	4	*Construction Material Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	*Deep Processing Industrial Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	*Equipment Manufacturing Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	*Hot Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0936	0	0	0	0.5600	0.9249	0	0	0	0	0.4827	1.0227
	8	*Iron Plant*	0	0	0.3173	0	0	0	0	0	0	0	0	0	0	0	1.2365	0	0.6722	0	0.0171	0	0	0	1.8695
	9	*Lime Plant*	0	0	0.0076	0	0	0	0	0	0.0067	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1642
	10	*Grid*	0	0	0.0036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
To	**11**	*On-Site Power Plant*	0	0	0.0013	0	0	0	0	0	0.0477	0	0.0745	0	0	0	0	0	0.2510	0	0	0	0	0	0
	12	*Scrap/Scale*	0	0	0	0.0173	0	0	0	0.0731	0	0	0	0	0	0	0	0	0	0.0212	0	0	0	0	0
	13	*Ship Building Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14	*Sinter Plant*	0	0	0.0538	0	0	0	0	0	0	0.0635	0	0	0.0154	0	0	0	0.0927	0	0	0	0	0	0.0012
	15	*Steel Plant*	0	0	0	0	0	0	0	0	1.0096	0.0808	0	0	0.0962	0	0	0	0.1146	0	0.0260	0	0	0	0.3272
	16	*Water Treatment Plant*	0	0	0	0	0	0	0	0	0	0	0	0.1498	0	0	0	0	0	0	0	0	0	0	1.5685
	17	*Wide & Heavy Plate Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0318	0	0	0	0.2450	0	0	0	0	0	0.2000	0.0556
	18	*Oxygen Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0431	0	0	0	0	0	0	0	0	0	0	0
	19	*Wetlands*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	20	*Pyrolysis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 18 - Current Structure and Flow Matrix of the Steel Manufacturing Process

APPENDIX C. EIP ANALYSIS SUPPLEMENTARY DATA

C.1 EIP Structure and Flow Matrix Construction

EIP Configuration			From																						
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Exports**	**Respiration**
To	**0**	*Imports*	0	0	0.6173	0	0	0	0	0	0.6904	0.2942	0.0709	0	0	0	1.0123	0	4.1200	0.0171	0	0	0	0	0
	1	*Cement Plant*	0	0	0	0	0	0	0	0	0.3481	0	0	0	0	0	0	0	0	0	0	0	0	0.3481	0
	2	*Coking Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6173	0	0	0	0	0	0.8510
	3	*Cold Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0562	0	0	0	0	0.0286	0	0	0	0	0.0675	0
	4	*Construction Material Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1250	0	0	0	0	0	0.1250	0
	5	*Deep Processing Industrial Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2000	0	0	0	0.2000	0
	6	*Equipment Manufacturing Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1142	0	0	0	0.1142	0
	7	*Hot Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0936	0	0	0	0.6000	0.9249	0	0	0	0	0.4827	1.0627
	8	*Iron Plant*	0	0	0.3173	0	0	0	0	0	0	0	0	0	0	0	1.2365	0	0.6722	0	0.0012	0	0	0	1.5055
	9	*Lime Plant*	0	0	0.0076	0	0	0	0	0	0.0067	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1642
	10	*Grid*	0	0	0.0036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11	*On-Site Power Plant*	0	0	0.0013	0	0	0	0	0	0.0477	0	0.0745	0	0	0	0	0	0.2510	0	0	0	0	0	0
	12	*Scrap/Scale*	0	0	0	0.0173	0	0	0	0.0731	0	0	0	0	0	0	0	0	0	0.0212	0	0	0	0	0
	13	*Ship Building Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0135	0	0	0	0.0135	0
	14	*Sinter Plant*	0	0	0.0538	0	0	0	0	0	0	0.0635	0	0	0.0154	0	0	0	0.0927	0	0	0	0	0	0.0012
	15	*Steel Plant*	0	0	0	0	0	0	0	0	1.0096	0.0808	0	0	0.0962	0	0	0	0.1146	0	0.0260	0	0	0	0.3022
	16	*Water Treatment Plant*	0	0	0	0	0	0	0	0	0	0	0	0.1498	0	0	0	0	0	0	0	0	0	0	1.5685
	17	*Wide & Heavy Plate Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0318	0	0	0	0.3000	0	0	0	0	0	0	0
	18	*Oxygen Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0431	0	0	0	0	0	0	0	0	0	0	0.0159
	19	*Wetlands*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	20	*Pyrolysis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 19 - Structure and Flow Matrix of the EIP Configuration in Steel Manufacturing

APPENDIX D. EIP EXPANSION SUPPLEMENTARY DATA

C.1 EIP Expansion Structure and Flow Matrix Construction

Expanded EIP Configuration			From																						
			0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Exports**	**Respiration**
To	**0**	*Imports*	0	0	0.2716	0	0	0	0	0	0.6759	0.2642	0.0574	0	0	0	0.9735	0	3.4506	0.0171	0	0	0	0	0
	1	*Cement Plant*	0	0	0	0	0	0	0	0	0.3481	0	0	0	0	0	0	0	0	0	0	0	0	0.3481	0
	2	*Coking Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5556	0	0	0.3457	0	0	0.7893
	3	*Cold Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0455	0	0	0	0	0.0257	0	0	0.1384	0	0.1923	0
	4	*Construction Material Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1250	0	0	0	0	0	0.1250	0
	5	*Deep Processing Industrial Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0.2000	0
	6	*Equipment Manufacturing Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1142	0	0	0	0.1142	0
	7	*Hot Rolling Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0758	0	0	0	0.6000	0.6000	0	0	0.0178	0	0.4827	0.7378
	8	*Iron Plant*	0	0	0.3173	0	0	0	0	0	0	0	0	0	0	0	1.2365	0	0.5800	0	0.0012	0.0672	0	0	1.4660
	9	*Lime Plant*	0	0	0.0076	0	0	0	0	0	0.0067	0	0	0	0	0	0	0	0	0	0	0.0300	0	0	0.1642
	10	*Grid*	0	0	0.0036	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11	*On-Site Power Plant*	0	0	0.0013	0	0	0	0	0	0.0477	0	0.0610	0	0	0	0	0	0.2259	0	0	0	0.0013	0	0
	12	*Scrap/Scale*	0	0	0	0.0173	0	0	0	0.0731	0	0	0	0	0	0	0	0	0	0.0212	0	0	0	0	0
	13	*Ship Building Plant*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0135	0	0	0	0.0135	0
	14	*Sinter Plant*	0	0	0.0538	0	0	0	0	0	0	0.0635	0	0	0.0154	0	0	0	0.0834	0	0	0.0481	0	0	0.0012
	15	*Steel Plant*	0	0	0	0	0	0	0	0	1.0096	0.0808	0	0	0.0962	0	0	0	0.1031	0	0.0260	0.0115	0	0	0.3022
	16	*Water Treatment Plant*	0	0	0	0	0	0	0	0	0	0	0	0.1213	0	0	0	0	0	0	0	0	0	0	0.7661
	17	*Wide & Heavy Plate Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0258	0	0	0	0.3	0	0	0	0.0060	0	0	0
	18	*Oxygen Plant*	0	0	0	0	0	0	0	0	0	0	0	0.0349	0	0	0	0	0	0	0	0	0	0	0.0077
	19	*Wetlands*	0	0	0	0	0	0	0	0	0	0	0	0.0339	0	0	0	0	0.6321	0	0	0	0	0	0
	20	*Pyrolysis*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0013	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 20 - Expanded EIP Material Flows and Structure in Steel Manufacturing

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